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Water immersion in athlete recovery a multi-disciplinary approach to informing practice

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**WATER IMMERSION IN ATHLETE RECOVERY:
A MULTI-DISCIPLINARY APPROACH
TO INFORMING PRACTICE**

SONYA JEAN MOORE

A thesis submitted for the degree of Doctorate in Health

University of Bath

Department for Health

February 2012

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S. J. Moore

ABSTRACT

Aims:

To explore and inform current water immersion recovery practice of high performance athletes; and to compare recovery interventions of 5 minutes cold water immersion, warm water immersion and passive rest, in trained subjects, following intense exercise replicating the demands of game-sports.

Methods:

Study 1: In a repeated measures design, a measurement approach for use in the evaluation of water immersion efficacy was piloted. The within-day and between-day reliability of surface electromyography (sEMG), particularly functional wavelet analysis, was evaluated in human lower limb muscles. Functional wavelet analysis provides the opportunity to measure neuromuscular function at the greatest level of detail by differentiating the relative intensity of low and high frequency motor unit recruitment. On 2 consecutive days (Trial 1 & Trial 2), 12 participants performed 3x5 second isometric 80% maximal voluntary contractions (MVC) on a Biodex[®] dynamometer in each of 15[°] ankle plantarflexion, 20[°] knee extension and 20[°] knee flexion. sEMG was obtained from the medial gastrocnemius (MG), vastus medialis (VM), vastus lateralis (VL) and biceps femoris (BF) muscles. Joint position and force production were controlled. Electrodes remained in situ during each trial. Electrodes were removed upon completion of Trial 1 and replaced in the same position the next day for Trial 2. Simultaneous sEMG metrics for intervals of consistent force production were compared between contractions in Trial 1 and Trial 2 (between-day) and contractions within Trial 2 (within-day).

Study 2: 11 trained participants completed the 90 minute Loughborough Intermittent Shuttle Test (LIST). Five minutes of COLD water immersion ($8.8 \pm 0.3^{\circ}\text{C}$), WARM water immersion ($35.1 \pm 1.8^{\circ}\text{C}$) and REST were compared in a repeated measures randomised cross over design. Recovery was evaluated at 2, 4 and 24 hours post exercise using circulating markers of muscle damage, muscle dynamometry, drop jump and repeated single leg hop performance tests and perceived recovery.

Study 3: Current water immersion practice of high performance athletes, practice implications stemming from this study's findings, and the rationale were explored. In a purposive, theoretical sampling approach of expert consultation, 8 professionals advising internationally competing athletes on water immersion recovery practice were provided with a research brief of this project in advance of a scribed, semi-structured interview. Participants were of Sports Coach, Strength & Conditioning Coach and Sports Physiotherapist professions with a minimum of 5 years' experience working with internationally competing athletes; and differed in international location and sporting disciplines.

Results:

Study 1: Functional wavelet analysis can resolve the high and low frequency spectrum within sEMG signal to represent the recruitment of fast and slow motor units in human lower limb muscles. During intervals of given force production, there was a high within-day percentage error in simultaneous sEMG metrics, which was more pronounced between days when electrodes were removed and replaced. This suggests the same force was produced using different patterns of neuromuscular recruitment. sEMG and functional wavelet analysis was therefore ultimately not determined sufficiently reliable for application in the evaluation of an intervention.

Study 2: There was a significant effect of intervention for lymphocytes ($p=.01$) but the pattern of decreased lymphocytes following water immersion compared to the control condition of rest was not significant (corrected $p=.08$). There was a time-intervention interaction for leukocytes ($p=.04$) but the observed decreased leukocytes at 24 hours following water immersion compared with the control condition of rest was not significant (corrected $p=.20$). There was a significant effect of intervention for Knee Extension (KE) Peak Torque ($p=.01$). Lower KE Peak Torque followed water immersion compared with the control condition of rest ($p<.01$), and lower KE Peak Torque followed cold water immersion compared with warm water immersion ($p=.01$). There was no significant effect of cold water immersion or warm water immersion on creatine kinase (CK), myoglobin, neutrophils; or variables relating to drop jump, single leg hop, perceived fatigue or perceived recovery. In terms of feeling recovered and prepared for athletic performance, there was a strong athlete preference for water immersion compared with rest, and warm was more often preferred than cold.

Study 3: Current water immersion practice in the high performance environment is based on athlete preference, speculative physiological effects and resource availability. Experts agreed that this study fulfilled the need to acknowledge the complexity of deciphering water immersion recovery intervention efficacy; particularly evaluation of a spectrum of outcome measures, proposed mechanisms of effect and implications for practice. The observations in this study were strong enough to influence practice decisions, supporting the continuation of water immersion recovery interventions with athlete preference as a determining factor.

Conclusion:

Current water immersion practice in the high performance environment is based on speculative physiological effects, resource availability and athlete preference. Athletes indicated a clear preference for water immersion over passive recovery and warm water was more often preferred than cold. Although there was evidence of a detrimental effect of water immersion in one muscle function variable (KE Peak Torque), there was no effect on any other variable amid a broad spectrum. It is therefore unclear whether this would impact athlete multi-skill performance. Judicious and sensible application of water immersion in athlete recovery is unlikely to be detrimental to overall performance and holistic recovery, however water immersion, particularly cold water immersion should be engaged cautiously closely preceding athletic participation. With a paucity of evidence demonstrating substantial physiological effects, athlete preference is a reasonable consideration in determining water immersion practice.

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TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	viii
LIST OF TABLES	xi
LIST OF EQUATIONS	xiii
Chapter 1 INTRODUCTION.....	1
1.1 Research overview.....	1
1.2 Research questions.....	2
1.3 Statement of purpose	3
1.4 Outline of study	5
1.5 Organisation of thesis	6
Chapter 2 REVIEW OF LITERATURE	8
2.1 Introduction.....	8
2.2 Literature review	9
2.2.1 Literature search strategy	9
2.2.2 Post-exercise response.....	10
2.2.3 Potential mechanisms and effects of water immersion on athlete recovery	15
2.2.4 Interventions to facilitate recovery.....	22
2.3 Summary of strengths and weaknesses in the current knowledge base.....	31
2.4 Chapter summary	32
Chapter 3 STUDY 1: METHOD DEVELOPMENT	33
3.1 Introduction.....	33
3.2 EMG-wavelet analysis in practice: Repeatability of measuring the relative recruitment of fast and slow twitch motor units during isometric MVC in human lower limb muscles.....	33
3.2.1 Introduction.....	33
3.2.2 Method.....	35

3.2.3	Results	37
3.2.4	Discussion	42
3.2.5	Conclusion	43
3.3	Chapter summary	43
Chapter 4 STUDY 2: THE EFFECT OF WATER IMMERSION ON RECOVERY FROM INTERMITTANT SHUTTLE RUNNING - STUDY DESIGN AND METHODS		44
4.1	Experimental design	44
4.2	Sample size	44
4.3	Ethics	45
4.4	Participants	45
4.5	Preliminary measures and familiarisation	46
4.6	Experimental protocol	47
4.6.1	Outcome measurement	47
4.6.2	Loughborough Intermittent Shuttle Test (LIST)	52
4.6.3	Intervention	55
4.6.4	Post intervention recovery monitoring	56
4.7	Data management	56
4.8	Data analysis	57
4.8.1	Statistical approach	57
4.8.2	Justification for statistical approach & management of multiple comparisons ..	58
Chapter 5 THE EFFECT OF WATER IMMERSION ON CIRCULATING MARKERS OF MUSCLE DAMAGE		60
5.1	Introduction	60
5.2	Method	60
5.3	Results	61
5.3.1	Evaluation of exercise (trial x time)	61
5.3.2	Evaluation of intervention (intervention x time)	62
5.3.3	Exploratory analysis	66
5.4	Discussion	67
5.5	Chapter summary	69
Chapter 6 THE EFFECT OF WATER IMMERSION ON NEUROMUSCULAR FUNCTION		70
6.1	Introduction	70
6.2	Method	72
6.2.1	Performance test data management	72
6.3	Results	81
6.3.1	Isometric Maximum Voluntary Contraction (MVC)	81

6.3.2	Drop Jump (DJ).....	84
6.3.3	Repeated Single Leg Hop (RH)	88
6.3.4	Exploratory analysis	91
6.4	Discussion.....	94
6.5	Chapter summary	100
Chapter 7	THE EFFECT OF WATER IMMERSION ON PERCEIVED RECOVERY.....	101
7.1	Introduction.....	101
7.2	Method	103
7.3	Results.....	103
7.3.1	Evaluation of exercise (trial x time).....	103
7.3.2	Evaluation of intervention (intervention x time)	103
7.4	Discussion.....	105
7.5	Chapter summary	106
Chapter 8	STUDY 3: WATER IMMERSION IN ATHLETE RECOVERY - APPLIED PRACTICE IN THE HIGH PERFORMANCE ENVIRONMENT	107
8.1	Introduction.....	107
8.2	Aim and objectives.....	108
8.3	Method	108
8.3.1	Participants.....	109
8.3.2	Research brief	110
8.3.3	Interview.....	110
8.3.4	Analysis.....	110
8.4	Results.....	111
8.4.1	Key themes underpinning recommendations for water immersion practice ...	111
8.4.2	Response to the research brief.....	116
8.5	Discussion.....	118
8.5.1	Implications for water immersion practice	118
8.5.2	Application of research to practice	119
8.6	Chapter summary	120
Chapter 9	GENERAL DISCUSSION - THE CONSTRUCTS OF RECOVERY, PERFORMANCE & PRACTICE	121
9.1	Introduction.....	121
9.2	General discussion and interpretation of key findings	122
9.2.1	Classification of main and exploratory variables	122
9.2.2	Interpretation of intervention effects and potential clinical implications	124
9.3	Summary of key findings.....	126

9.4	Response to research questions.....	127
9.5	How this study has contributed to the knowledge base	131
9.6	Methodological considerations and future directions	132
9.7	Thesis conclusion	136
Chapter 10	REFERENCES.....	138
APPENDICES.....		148
Appendix 1 - Within-subject maximum voluntary contraction (MVC) Knee Flexion Peak Torque at 20° – between-day mean and standard deviation		
		152
Appendix 2 – Water immersion in athlete recovery (WIAR) project: record of intervention water temperatures		
		153
Appendix 3 – Expert consultation: Research brief		
		154
Appendix 4 – Expert consultation: Common interview format		
		171

LIST OF FIGURES

Figure 1.1 Water immersion in athlete recovery: a schematic representation of the study design	6
Figure 2.1 Key events following exercise induced muscle damage.	11
Figure 2.2 Key mechanisms of fatigue	13
Figure 2.3 Potential physiological effects of water immersion: mechanisms of hydrostatic pressure and whole body cutaneous thermo-receptor stimulation (cold) and an indicative time-response gradient. Potential responses to water immersion are duration and temperature dependent. An indicative time-response gradient is shown. Independent of temperature, hydrostatic pressure induces a cascade of physiological effects. In addition, cold water immersion launches a temperature- response cascade. Therefore the influence on athlete recovery is likely to be protocol-specific, and there are likely to be additional effects of cold compared to thermo-neutral water immersion. Likely end effects which could influence athlete recovery are shown in bold-box.	20
Figure 3.1 RMS value of the EMG signal - trial mean and 95% CI for muscles a) MG, b) VL, c) VM, d) BF	37
Figure 3.2 iEMG value of the EMG signal - trial mean and 95% CI for muscles a) MG, b) VL, c) VM, d) BF	38
Figure 3.3 iWR value of the EMG signal - trial mean and 95% CI for muscles a) MG, b) VL, c) VM, d) BF	38
Figure 3.4 Mean intensities of the 11-wavelet bank and slow/fast motor unit representation for muscles a) MG, b) VL, c) VM, d) BF	39
Figure 4.1 Muscle dynamometry test positions: a) Isometric KF at 20°, b) Isometric KE at 60°	49
Figure 4.2 Force plate drop jump (DJ): starting position on a 30cm high box prior to step off; and contact phase	50
Figure 4.3: Force plate repeated single leg hop starting position	51
Figure 4.4 Schematic representation of The Loughborough Intermittent Shuttle Test (LIST)	52
Figure 4.5 Percentage change in mean 15m sprint time for each of the 6 LIST sub-cycles for Trial 1, Trial 2 & Trial 3	54
Figure 4.6 Schematic representation of the statistical approach to data analysis	58
Figure 5.1 Venous leukocytes percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	62
Figure 5.2 Venous neutrophils percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	63
Figure 5.3 Venous lymphocytes percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	63
Figure 5.4 Venous creatine kinase percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	64
Figure 5.5 Venous myoglobin percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	64
Figure 6.1 Drop Jump Contact Time: illustration of a Ground Reaction Force (GRF)-time (t) curve, $F(t)$	73
Figure 6.2 Drop Jump Contact Time: illustration of an acceleration-time curve, $a(t)$	76
Figure 6.3 Drop Jump Contact Time: illustration of a velocity-time curve, $v(t)$	76
Figure 6.4 Drop Jump Contact Time: illustration of a power-time curve, $P(t)$	77

Figure 6.5 Illustration of the relationship of the power-time curve, $P(t)$, to the variable work, $\int P(t)$.	78
Figure 6.6 Components of work performed during the Drop Jump	79
Figure 6.7: Illustration of sequential hop landing loci and displacement	80
Figure 6.8 Knee Flexion (KF) Peak Torque percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	82
Figure 6.9 Knee Extension (KE) Peak Torque percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	82
Figure 6.10 Jump Height percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	85
Figure 6.11 Reactive Index: percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	86
Figure 6.12 Jump Work _{neg} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	86
Figure 6.13 Jump Work _{abs} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	87
Figure 6.14 Jump Peak Power _{neg} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	87
Figure 6.15 Hop Work _{abs} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	89
Figure 6.16 Hop Height _{tot} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	90
Figure 6.17 Hop Flight Time _{tot} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	90
Figure 6.18 Correlation of Jump Height with Functional Performance Indicators: Jump Work _{abs} (J), KF Peak Torque (N.m) & KE Peak Torque (N.m)	92
Figure 6.19 The percentage change in mean from Pre-Exercise in performance indicators Jump Height and Hop Height and selected clinically relevant variables with a significant Post Exercise change in the control trial of rest.	93
Figure 7.1 Rating of Perceived Fatigue (PF) in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	104
Figure 7.2 Rating of Perceived Recovery (PR) in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions	104
Figure 7.3 Percentage (%) distribution of nominated Preferred and Least Preferred recovery interventions of 5 minutes cold water immersion, warm water immersion and rest	105
Figure 9.1 Schematic representation of application of study design & results to water immersion practice	131

LIST OF TABLES

Table 2.1 Water immersion in athlete recovery: summary of key publications informing this project	27
Table 3.1 Percentage error of reproducing the pre-calculated 80% MVC in different trials	37
Table 3.2 Between-trial reliability of root-mean-square (RMS), integrated (iEMG) and slow:fast wavelet intensity ratio (iWR) metrics of the EMG signal for muscles MG, VL, VM & BF: typical error, confidence interval, ICC and paired t-test.	41
Table 4.1 Relevant participant characteristics	45
Table 4.2 LIST Rating of Perceived Exertion (RPE) for Trial 1, Trial 2 and Trial 3	54
Table 4.3 Randomised counterbalanced intervention sequence	55
Table 4.4 Intervention ambient and water temperatures ($^{\circ}\text{C}$)	56
Table 5.1 Pre- and Post- Exercise means and mean % change in circulating markers of muscle damage for Trials 1, 2 and 3	61
Table 5.2 Circulating markers of muscle damage following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest	62
Table 5.3 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for venous leukocytes, following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest	65
Table 5.4 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for venous lymphocytes, following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest	66
Table 5.5 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons of Pre-Exercise (Pre-Ex) with 4 hours and 24 hour levels of time for venous neutrophils, CK and myoglobin in the control condition of rest	66
Table 6.1 Percentage change in Pre- and Post-Exercise Knee Flexion (KF) & Knee Extension (KE) peak torque	81
Table 6.2 Knee Flexion (KF) Peak Torque and Knee Extension (KE) Peak Torque following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest	81
Table 6.3 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for Knee Extension (KE) Peak Torque, following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest	83
Table 6.4 Drop Jump variables: Pre- and Post- Exercise means for Trials 1, 2 and 3 and mean % change	84
Table 6.5 Drop Jump variables following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest	85
Table 6.6 Repeated Single Leg Hop (RH) percentage change Pre- and Post-Exercise	88
Table 6.7 Repeated Single Leg Hop (RH) variables following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest	88
Table 6.8 Correlation of the performance indicator Jump Height with potentially contributing variables	91
Table 6.9 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons of Pre-Exercise (Pre-Ex) with 2 hours, 4 hours and 24 hour levels of time for KF Peak Torque, Jump Work _{abs} , and Hop Work _{abs} in the control condition of rest	94
Table 8.1 Characteristics of consulted experts	109

Table 9.1 Summary of statistical results: classification of main and exploratory variables according to their sensitivity to change over time, Pre-Post Exercise change and significance of pre-planned statistical comparison for intervention effects	123
Table 9.2 Observed influence of water immersion	126
Table 9.3 Summary of Practice Recommendations based on study findings	130

LIST OF EQUATIONS

Equation 1: Calculation of take-off velocity (v_{to})	74
Equation 2: Calculation of vertical displacement at a given time point ($x(t)$)	74
Equation 3: Calculation of Jump Height from the point of maximum displacement	75
Equation 4: Calculation of the acceleration-time curve, $A(t)$, and velocity-time curve, $v(t)$	75
Equation 5: Calculation of Work	77

Chapter 1 INTRODUCTION

1.1 Research overview

Water immersion is a common practice aimed at enhancing athlete recovery from intense exercise, but is largely based on anecdotal evidence (Barnett, 2006; Wilcock, Cronin & Hing, 2006). While the physiological effects of sustained water immersion are well understood (Pendergast & Lundgren, 2009), it is not clear how the scientific rationale applies specifically to athlete recovery (Bleakley & Davidson, 2010; Cochrane, 2004). The intentions include attenuating post-exercise muscle damage and inflammation, facilitating metabolic and neuromuscular recuperation, and promoting relaxation. The speed of recovery to a pre-exercise state of health is particularly important to athletes, who seek to participate in successive training and competitions with maximum performance.

Several studies have observed favourable effects of water immersion over passive rest. These include improved muscle power, stiffness and soreness following aquatic exercise (Takahashi, Ishihara & Aoki, 2006) and improved loaded squat jump performance, improved isometric strength, decreased creatine kinase (CK) and decreased perceived pain (Vaile, Halson, Gill & Dawson, 2008). Rowsell, Coutts, Reaburn & Hill-Hass (2009) showed less muscle soreness and general fatigue following cold water immersion, but no difference in any physiological measures.

Particularly, there is a paucity of empirical evidence supporting water immersion protocols in the order of 5 minutes duration, which are typical of current practice (Peterson, 2006; Sellwood, Brukner, Williams, Nicol & Hinman, 2007; Snelling, 2006). Recent studies have shown no effect of short duration water immersion on post-exercise markers of muscle damage CK and myoglobin (Ingram, Dawson, Goodman, Wallman & Beilby, 2009; Roswell, et al., 2009; Sellwood, Brukner, Williams, Nicol & Hinman, 2007). However, two studies have reported benefits of 10-14 minutes of water immersion compared to passive recovery. Bailey, Erith, Griffin, Dowson, Brewer, Gant & Williams (2007) showed no change in CK, but decreased myoglobin peak following cold water immersion. Conversely, Vaile et al., (2008) observed no change in myoglobin but significant reductions in CK activity following cold water immersion and at 48 hours following warm water immersion.

Although some studies have shown no difference between water immersion of different temperatures (Sellwood et al., 2007), it is likely that temperature is important. Detrimental effects of cold water immersion have been proposed, although not substantiated following short duration immersion. Hyperthermia-induced training adaptations could be attenuated (Snelling, 2006; Yamane, Teruya, Nakano, Ogai, Ohnishi & Kosaka, 2006); while cold application has been shown to slow nerve conduction velocity (Algafly & George, 2007), reduce agility (Evans, Ingersoll, Knight & Worrell, 1995), impair vertical jump and sprint performance (Cross, Wilson, & Perrin, 1996) and reduce knee extension maximum voluntary contraction (MVC) (Pfeiffer, Abbiss, Nosaka, Peake & Laursen, 2008). Conversely, Bailey et al., (2007) concluded that 10 minutes of cold water immersion facilitated knee flexion strength at 24 and 48 hours;

and Ingram et al., (2009) reported that strength losses at 48 hours following hot / cold contrast immersion and passive recovery were not seen following 15 minutes of cold water immersion. Research has not evaluated whether short duration immersion could facilitate recovery whilst avoiding potential counterproductive effects of extreme temperature exposure.

Consolidation of these research findings and application to practice is challenging as they evaluate different water immersion protocols, using a variety of outcome measures following diverse exercise tests. Deciphering the implications for water immersion practice in athlete recovery is further complicated by speculative rather than established mechanisms of effect. With the intention of engaging best practice, practice decisions are made in a complex way (Amonette, English & Ottenbacher, 2010; Sackett, Rosenberg, Gray, Haynes & Richardson, 1996). Best practice is difficult to define unless the scientific evidence is convincing, and interpretative mechanisms could have contributed to the variety of protocols in common practice (Chapter 8).

Although the influence on athlete recovery remains speculative, hydrostatic pressure and temperature effects are the proposed mechanisms of water immersion. Hydrostatic pressure centralises blood volume over time, and the circulatory effects are purported to both attenuate cellular extravasation and facilitate muscular perfusion (Pendergast & Lundgren, 2009). Decreased muscle spasm, increased cellular metabolism and vasodilation accompanying warm water immersion could increase oxygen supply to the tissues and reduce secondary hypoxic damage (MacAuley, 2001) while cold water immersion could attenuate the post exercise inflammatory response through vasoconstriction, reduced tissue metabolism and consequently reduced secondary hypoxic cellular damage (Brukner and Khan, 2007). Mechanisms of effect are discussed fully in Chapter 2.

The current evidence base explores a range of protocol including varied temperatures, immersion times, depths, exercise protocols and outcome measures. This has contributed to a body of varied findings, making between-study comparisons difficult and further clouding potential mechanisms of effect. Further research is needed to clarify previous findings, evaluate current practice and decipher the influence on athletic performance and functional implications for athletes. There is a need to evaluate the time-course of recovery integrating the spectrum of contributory physiological, functional and psychological outcome measures, including an overarching consideration of practice implications. The degree of recovery and effect of water immersion intervention at time-points where athletes are likely to embark on subsequent training or competition activity requires particular focus.

1.2 Research questions

i. What is the expected time-course of recovery without intervention?

Plotting the expected post-exercise response and recovery timeline is important for athletes engaging in subsequent exercise bouts; training or competition. To allow meaningful interpretation of intervention effects, it is necessary to first understand the expected time-course of recovery to a pre-exercise state without intervention. A suitable fatigue platform

which induces decline in athletic performance enables generation of the expected recovery time-course for a spectrum of recovery indicators.

ii. Does 5 minutes of water immersion alter the expected time-course of recovery?

Water immersion is commonly utilised by athletes to improve the degree and speed of recovery. There is strong anecdotal support but equivocal evidence to support this current practice. Most research has investigated the effects of sustained immersion times of 15-20 minutes, often in untrained athletes, although shorter immersion time is more typical of current practice. In trained athletes, the effects of 5 minute water immersion, and the influence on the time-course of recovery to a pre-exercise state have not been established.

iii. Are there different effects of warm and cold water immersion?

Physiological effects of water immersion are temperature dependent (Chapter 2, 2.2.3). Different effects of warm and cold water immersion which could facilitate or impair recovery athlete recovery have been proposed but not clearly established.

iv. Of the spectrum of outcome measures, which recovery indices are most valued in making practice decisions?

Fatigue and recovery are multi-systemic and multi-factorial; integrating physiology, neuromuscular function, perception and athletic performance constructs. To provide the best advice to athletes, the effect of water immersion on these constructs must be understood independently and holistically. Grounding practice decisions requires selection of outcome measures that are reliable, valid and have the strongest relationship with athletic performance.

v. What are the recommendations for water immersion practice which stem from this study?

The influence of study outcomes on water immersion practice is central to this multi-disciplinary project within a Professional Doctorate. Given the disparity between commonality of water immersion recovery interventions and supporting evidence, this project aimed to replicate, investigate and provide recommendations for current practice. The typical athlete recovery regime utilising the purpose built hydrotherapy facility at the University of Bath has not been specifically tested.

1.3 Statement of purpose

Aim

The aim of this project was to explore and inform current water immersion recovery practice of high performance athletes; and to compare recovery interventions of 5 minutes cold water immersion, warm water immersion and passive rest, in trained subjects, following intense exercise replicating the demands of game sports.

Objectives

1. To evaluate the effects of water immersion recovery interventions on athlete recovery from intense exercise at different post-exercise time-points
2. To establish the effects of water immersion on physiological recovery
3. To establish the effects of water immersion on recovery of neuromuscular function
4. To establish perceived recovery following water immersion
5. To establish whether there is a relationship between physiological, neuromuscular function and perceived measures of recovery, as indicators of overall athlete recovery
6. To explore current water immersion practice of high performance athletes, and the rationale
7. To explore how evidence relating to water immersion recovery practice is valued and applied by practice experts
8. To formulate water immersion practice recommendations based on the findings of this study

Purpose & Hypotheses

The purpose of this research was to compare physiological recovery, neuromuscular function and perceived recovery following cold water immersion, warm water immersion and rest. It was hypothesised that water immersion facilitates recovery compared to passive rest.

A secondary hypothesis was that cold water immersion is detrimental to same-day recovery. This was underpinned by anecdotal avoidance of cold water immersion closely preceding athletic participation (Chapter 8).

Philosophy

Sport science and medicine research demands robust experimental design and statistical analysis alongside consideration of clinical significance, including critical recommendations for practice. The body of literature surrounding water immersion recovery interventions is largely grounded in positivist experimental research designs. Although implied rather than explicit, there is broader support for a critical realist perspective of performance and recovery through the investigation of interacting physiological and social factors.

This study independently scrutinised physiological, neuromuscular and perceived elements of the post-exercise response and recovery time-course. Deciphering the implications for water immersion practice required further scrutiny of their relationship with each other and to performance; and their relative value to practitioners. This recognises the constructivist perspective to recovery and performance.

The project is positioned in the post positivist paradigm. The exact nature of sport science has positivist elements however sport performance is viewed as a construct of several independent and inter-dependent variables. A critical realist perspective captures the central scientific philosophy of human physiology, whilst recognising the need to evaluate several variables when measuring and quantifying athlete fatigue and recovery; and making practice decisions.

1.4 Outline of study

To substantiate current practice, this study compared the effects of 5 minutes of warm water immersion, cold water immersion and a control group; on circulating markers of muscle damage, neuromuscular function, perceived recovery and overall recovery; following intense exercise replicating that of game-sport athletes.

Although the effects of longer duration water immersion are established and shorter duration is speculative, 5 minutes of water immersion replicates a duration typical of common practice, and is a realistic timeframe of cold water immersion tolerated by athletes.

Recovery of trained athletes was evaluated following the 90 minute Loughborough Intermittent Shuttle Test (LIST) which replicates the demands of team sports. Many previous studies have investigated responses to unaccustomed exercise, as a larger effect size may be anticipated and small effects identified. However, this does not replicate the possible effects on accustomed athletes who are familiar with a range of recovery interventions. This study specifically included athletes who habitually compete in high intensity exercise similar to the LIST and were regular users of water immersion recovery. Although this may have decreased the size of the effect, for external validity and application to the athletic community it was necessary to replicate this familiarity.

Recovery was evaluated at 2 hours, 4 hours and 24 hours post-exercise, which are time-points likely to coincide with potential participation in subsequent exercise bouts. Figure 1.1 is a schematic representation of the study design.

Selection of outcome measures

The effects of water immersion suggest a spectrum of potential outcome measures is necessary to evaluate the effect on recovery. Previous studies have evaluated blood variables following cold or warm water immersion but few have evaluated the effect following a combination of intense prolonged exercise *and* a spectrum of variables. CK is often an indicator of muscle damage and therefore recovery (Gill, Beaven & Cook, 2006; Roswell et al., 2007; Sellwood et al., 2007; Takahashi et al., 2006; Vaile et al., 2007), although it does not correlate strongly with muscle soreness (Ingram et al., 2009; Thompson, Nicholas & Williams, 1999) or impaired neuromuscular performance (Rodenburg, Bar & De Boer, 1993). It is worthwhile investigating the effects of water immersion on different blood cell sub-populations *alongside* functional implications for athletes.

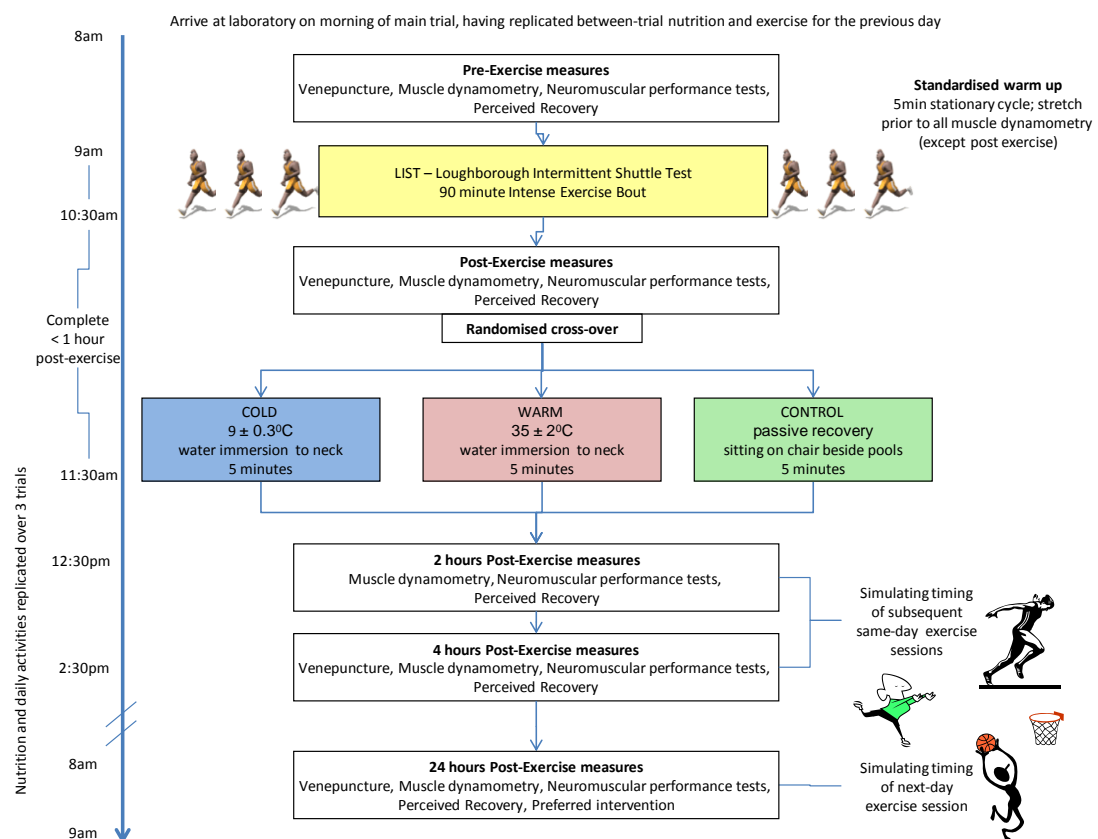
Most studies consider function as muscle force measures (Rodenburg et al., 1993; Thompson, Williams, Garcia-Roves, McGregor, McArdle & Jackson, 2003) which does not account for co-ordination or skill execution. This study evaluated neuromuscular function based on force generation capacity alongside functional performance measures.

As the links between laboratory outcome measures and athletic performance per se are assumptive, a key objective of this study was to explore the correlation between empirical and

constructive outcome measures. Perceived recovery was therefore included as a key component of holistic recovery.

Figure 1.1 Water immersion in athlete recovery: a schematic representation of the study design

A schematic representation of the study design alongside an indicative timeline of the trial conditions is shown. Recovery of trained athletes was evaluated following the 90 minute Loughborough Intermittent Shuttle Test (LIST). In a randomised cross over design, interventions of 5 minutes cold water immersion, 5 minutes warm water immersion and a control group (rest) were compared. Post exercise measures were evaluated at 2 hours, 4 hours and 24 hours post-exercise, which are time-points likely to coincide with potential participation in subsequent exercise bouts. The project endeavoured to replicate typical daily timing of athlete activities while maintaining controlled testing conditions. Key features of this intention are annotated.



1.5 Organisation of thesis

Following an in-depth review of literature in Chapter 2, the methodologies of the main project are described in Chapter 4. Participant characteristics and test-exercise performance are described in particular detail as this was central to establishing external validity to the target population of trained athletes undertaking intense exercise.

Chapter 3 summarises the reliability study of an intended methodology, which was not ultimately considered adequately reliable for application in the main study.

Human function and athletic performance are underpinned by integrated physiology, and this project evaluated the efficacy of water immersion recovery practice based on a spectrum of variables representing physiological, neuromuscular function and perceived recovery. To facilitate detailed discussion and preserve clarity, project endeavours specific to these subsidiary systems are independently scrutinised and presented in Chapter 5, Chapter 6 and Chapter 7. Chapter 9 then explores the integrated relationship between systems and variables and addresses the overarching implications for water immersion practice.

Chapter 8 presents a qualitative study exploring current water immersion recovery practice of high performance athletes. This includes exploring how the evidence is valued and applied by practice experts, including the implications of the findings of this project.

The key results of this project are presented and research questions are answered in Chapter 9, including interpretation of intervention effects, potential clinical implications and practice recommendations. A summary of methodological considerations and future directions for research follows. This chapter concludes the thesis.

Chapter 2 REVIEW OF LITERATURE

2.1 Introduction

The benefits of regular exercise are well established and encouraging physical activity forms part of the World Health Organisation (WHO) global health strategy (WHO, 2004). Within this broader context, high performance athletes experience large exercise volumes which are associated with increased injury risks (Jones, Cowan & Knapik, 1994), fatigue and performance decline (Halsen & Jeukendrup, 2004) and immune suppression (Gleeson, 2007; Nieman & Pederson, 1999). The sport science and medicine community must therefore scrupulously manage training loads and recovery of athletes participating in intense and successive exercise bouts to realise both optimal training adaptations and peak physical condition. This demands critical evaluation of the typical post exercise response, recovery process and interventions which may desirably influence these.

Intense exercise challenges the metabolic, nervous, endocrine and musculoskeletal systems (Reilly & Ekblom, 2005), culminating in muscle function decline and decreased performance (Allen & Westerblad, 2004). Fatigue mechanisms and exercise performance limitations are multi-systemic and integrative, including systems physiology of neuromuscular activation, metabolism and temperature homeostasis, and the “psyche” (Hargreaves, 2008). Although scrutiny of these subsidiary components is essential in building a profile of fatigue and recovery, their intricate and complex relationship must be appreciated. Full recovery involves recuperation of these systems and is important in returning athletic performance potential.

There are two defining elements of recovery: the restoration to the pre-exercise state of health and the time course over which this occurs. The degree and speed of recovery following intense exercise is particularly important to athletes, who seek to participate in successive training and competitions with maximum performance. A small advantage can be the difference between winning and losing, and athletes undertake a range of interventions with the aim of facilitating recovery.

The aim of recovery interventions is to counteract fatigue-related changes or facilitate their return to pre-exercise levels, although the precise ambition could be different following training or competition. Interventions which limit initial muscle damage and attenuate the post-exercise inflammatory response could curtail secondary muscle damage (St. Pierre Schneider & Tiidus, 2007; Tiidus, 2005) and facilitate the recovery process during competition. However this response also forms the initial stages of repair, adaptation and immune defence (Braun & von Duvillard, 2004; Lagranha, Levada-Pires, Sellitti, Procopio, Curi & Pithon-Curi, 2008), thus attenuation may be less desirable during training phases. Recovery is therefore measurable using an array of outcome measures representing muscle damage, inflammation, immune function and neuromuscular function. For athletes seeking to participate in successive exercise bouts, it is reasonable to assume that restoration of pre-exercise status as rapidly as possible is the desired effect.

2.2 Literature review

Water immersion is commonly utilised by athletes with the aim of facilitating recovery from training and competition. Speculative theory supports this practice but its efficacy has not been substantiated by research. The mechanisms underpinning recovery can best be grounded in the evidence describing typical post-exercise expectations. These mechanisms are complex and significant debate surrounds the relevance and specificity of the direct measure and indirect indicator spectrum. Discerning selection of outcome measures which best reflect the potential for athletic performance is required to determine water immersion efficacy.

Firstly, this review appraises the typical post-exercise response which presents indicators of fatigue and recovery, many of which are targeted by recovery-facilitating interventions. Secondly, the mechanisms by which water immersion could facilitate recovery are discussed. This prefaces a critical review of the practice and evidence surrounding water immersion in athlete recovery.

The body of evidence is broadly grounded in the positivist paradigm, evaluating causality of recovery interventions through experimental designs. Sports science and medicine requires rigorous evaluation of empirical data to justify practice, although the constructivist nature of athletic performance and recovery should also be recognised.

2.2.1 Literature search strategy

A primary search of electronic databases PubMed, SPORTDiscus™ and Science Direct was undertaken using key words *athlete*, *recovery*, *hydrotherapy*, *pool*, *bath*, *ice*, *contrast* and *immersion*. This project's focus was the application of water immersion in athlete recovery; in the practice context of post-exercise recovery of healthy high performance athletes. Therefore publications with primary focus on medical conditions, veterinary based titles, poolside risk evaluation, spinal deformity, concussion and injury rehabilitation were excluded. 50 relevant publications were categorised according to focus areas: water immersion in the context of athlete recovery intervention practice ($n=19$), physiological response to water immersion ($n=11$), physiological response to temperature ($n=15$), active recovery interventions other than water immersion ($n=5$). These articles were critically reviewed.

A summary of publications relating to the effects of water immersion in the context of athlete recovery intervention practice is presented in Table 2.1, including study design, methods and outcomes. Review publications ($n=4$), including the type of review, were differentiated from publications with experimental designs ($n=15$). Of the experimental designs, firstly studies most closely replicating the demands on athletes and recovery from intense exercise were identified ($n=6$). Secondly, studies describing alternate research and exercise protocols but with findings relevant to informing this project were identified ($n=9$).

The topic of water immersion in athlete recovery is an area of practice undergoing continual discussion, scrutiny and development. Therefore, the literature search was supplemented with consultation of recovery guidelines provided to athletes by National Governing Bodies of

Sport, text books recommended to post-graduate sports medicine and sports physiotherapy students and conversation with prominent researchers in the field regarding studies unpublished and in progress. Reference lists of key publications were scrutinised to ensure all relevant publications had been considered and original research sources consulted.

The literature surrounding water immersion practice in athlete recovery did not elucidate proposed mechanisms of effect in sufficient detail. Therefore further literature searches exploring speculative mechanisms of effect were undertaken. A search of the PubMed database including key terms *hydrostatic pressure* and *effects* returned a series of articles relating to the effects of hydrostatic pressure in deep sea diving, which enabled more detailed scrutiny of the effects of water immersion over time (independent of water temperature). A search of the PubMed database for the term *cryotherapy* returned 2 systematic review publications critically reviewing the original research surrounding ice therapy. These publications were critically reviewed, the reference lists scrutinised and relevant primary research sources consulted. This enabled more detailed scrutiny of potential effects of cold application over time, which was relevant in proposing potential effects of cold water immersion.

A search of the PubMed database including key terms *fatigue* and *mechanisms* returned a series of 10 relevant publications providing high quality reviews of primary research ($n=9$) and current interpretation ($n=1$) of fatigue mechanisms, integrative physiology and the determination of exercise performance. These publications were authored by prominent researchers in the field. This perspective and consultation of relevant primary research in the reference lists underpins discussion of the post-exercise response which provides the grounding for recovery mechanisms.

These literature search strategies were saved and included consideration of publications recent to submission of this thesis.

2.2.2 Post-exercise response

Fatigue mechanisms and exercise performance limitations are multi-systemic and integrative, including systems physiology of neuromuscular activation, metabolism and temperature homeostasis, and the “psyche” (Hargreaves, 2008). Muscle fatigue can be defined as exercise-induced reduction in maximal voluntary muscle force (Gandevia, 2001; Lattier, Millet, Martin & Martin, 2004) attributable to changes in the central nervous system (CNS) drive to the motor neurons (Gandevia, 2001; Hargreaves, 2008) or peripheral changes in the muscular force producing capacity and patterning at muscular level (St. Clair Gibson & Noakes, 2004). Models of post-exercise local muscle damage describe key stages of initial events, autogenic processes, phagocytosis and regeneration (Armstrong, 1990). Figure 2.1 illustrates the cascade of events associated with exercise induced muscle damage.

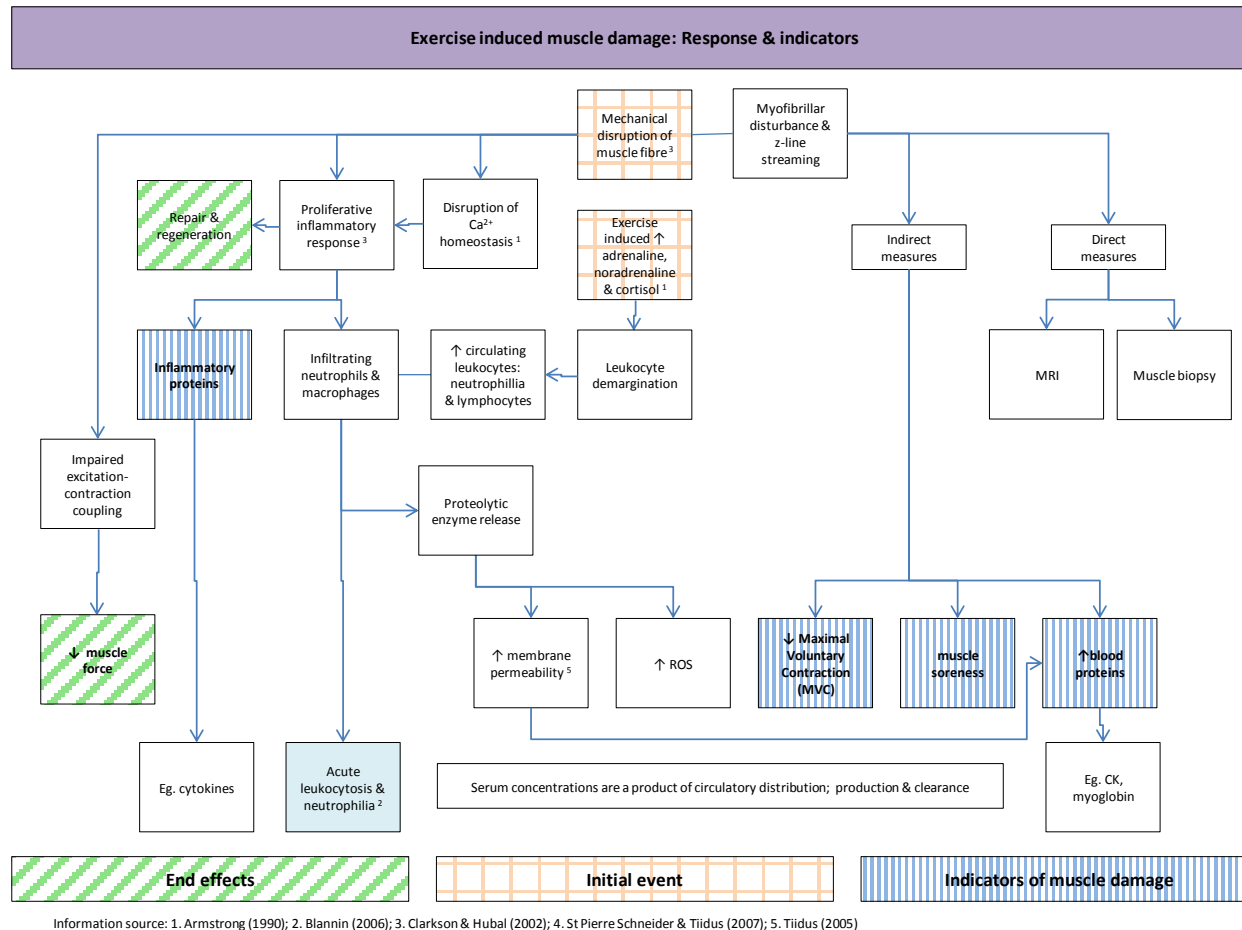


Figure 2.1 Key events following exercise induced muscle damage.

Key initial events, end effects and indicators of muscle damage following exercise are denoted. Mechanical disruption of muscle fibres characterises exercise induced muscle damage, which initiates trans-membrane cellular changes and an inflammatory cascade response. Muscle damage is measurable through direct measures of myofibre disruption; cellular indicators of altered membrane permeability and the inflammatory response; and resultant effects on muscle contractile function.

Mechanical disruption of sarcomere myofilaments and disruption of calcium homeostasis across cellular membranes is followed by an inflammatory and immune response (Armstrong, 1990; Kendall & Eston, 2002) and release of cytosolic enzymes such as CK (Warren, Lowe & Armstrong, 1999). Lactic acid accumulation has been associated with muscle acidosis leading to transient impairment of contraction capacity and muscle soreness (Allen & Westerblad, 2004). These therefore provide common indices of exercise induced muscle damage and recovery (Warren et al., 1999).

The post-exercise inflammatory response is typified by an increase in circulating neutrophils and lymphocytes (Gleeson, 2007) and a subsequent lymphocytopenia (Nieman et al., 1994). Release of adrenaline and noradrenaline by the sympathetic nervous system (SNS) during exercise stimulates leukocyte demargination and release from the spleen resulting in an acute leukocytosis (Blannin, 2006). Exercise above 60% VO_2max stimulates cortisol release from the hypothalamus, mobilising leukocytes from the bone marrow (Blannin, 2006) and increasing bone marrow production resulting in delayed leukocytosis (Lagranha et al., 2008). While their extravasation at the site of injury is the first part of the proliferative inflammatory response (St. Pierre Scneider & Tiidus, 2007), venous leukocyte levels are representative of the distribution between the organs and circulation (Pedersen, Rohde & Ostrowski, 1998).

Eccentric exercise is particularly associated with significant post-exercise microscopic muscle and tendon damage (Pull & Ranson, 2007) and Delayed Onset Muscle Soreness (DOMS) describes the typical muscle soreness most frequently experienced in response to unfamiliar eccentric exercise (Cheung, Hume & Maxwell, 2003). However athletes participate in intense exercise patterns of which eccentric exercise and muscle damage is only one component. Intense exercise can be described as strenuous intermittent exercise with high oxygen consumption and high energy expenditure; this is typical of many team sports.

Previous focus has been on the resultant depletion of metabolic substrates and the accumulation of metabolic by-product (Hargreaves, 2008), although more recently the cascade of multi-organ, multi-cellular and multi-molecular events are recognised (McKenna & Hargreaves, 2008). Figure 2.2 presents these key mechanisms of central and peripheral fatigue which become targets for athlete recovery.

Neuromuscular muscle function can be impaired by exercise-related decreased cerebral oxygenation (Secher, Seifert & Van Lieshout, 2007), altered neurotransmitter release (Brukner & Khan, 2007), Na^+ and K^+ perturbations contributing to decreased cellular membrane excitability (McKenna, Bangsbo & Renaud, 2007) and excitation-contraction coupling fatigue (Lattier et al., 2004). Failure of sarcoplasmic reticulum Ca^{2+} release (Allen, Lamb & Westerblad, 2007), impaired cross-bridge interactions (Fitts, 2008) and increased reactive oxygen species (ROS) (Ferriera & Reid, 2007) can reduce force production in contracting muscles. These mechanisms operate within complex feedback and feed-forward systems governing neuromuscular activation (Hargreaves, 2008).

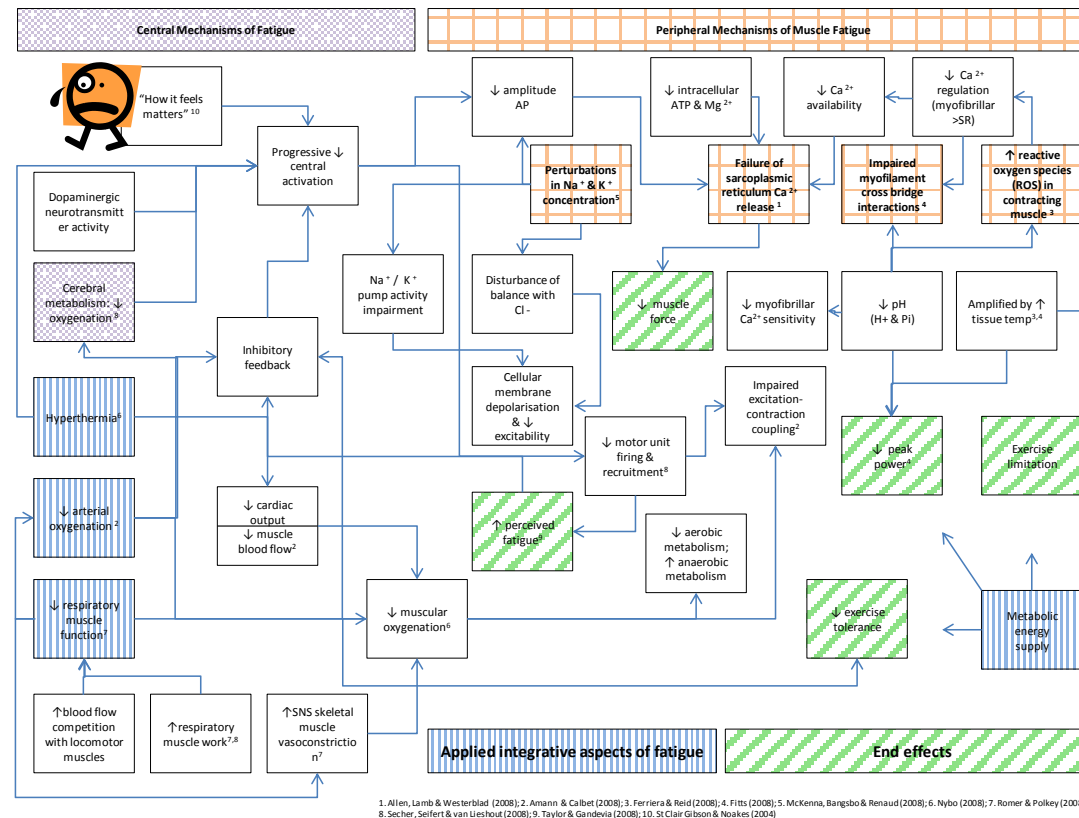


Figure 2.2 Key mechanisms of fatigue

Mechanisms of fatigue can be broadly categorised as central or peripheral, representing the post-exercise response cascade at systemic and central nervous system levels (central) and at the level of the muscle (peripheral). However the complex feedback and feed-forward cellular responses to exercise are indicative of the integrative nature of systems physiology, resulting in a spectrum of measurable cellular and end-effect exercise performance indicators.

The central nervous system also requires a glycogen supply to maintain neural drive to the muscles (Nybo, 2003) and at the muscular level glycogen availability effects sarcoplasmic reticulum Ca^{2+} release and excitation-contraction coupling (Chin & Allen, 1997). Furthermore inflammatory cells compete with muscle fibres for blood glucose, reducing the availability of glucose for energy production and replenishment of glycogen stores (Costill, Pascoe & Fink, 1990; Gillum, Dumke & Ruby, 2006). When energy generation fails to keep up with demand fatigue and decreased performance results (McArdle, Katch & Katch, 2007).

Other limitations on prolonged exercise performance include exercise induced hyperthermia (Nybo, 2007), decreased arterial oxygenation (Amman & Calbet, 2007) and decreased respiratory function (Romer & Polkey, 2007), which have integrated effects on central and peripheral fatigue mechanisms (McKenna & Hargreaves, 2008).

It is unlikely that a state of 'fatigue' can be attributed to isolated mechanisms (Hargreaves, 2008) and it is the end effect of fatigue mechanisms that are of primary interest to the athletic community. Post-exercise physiological manifestations include muscle soreness, muscle stiffness, decreased flexibility and slowed reaction time (Byrne & Eston, 2002; Takahashi Ischarat & Aoki, 2006). Athletic skill performance is the construct of multiple phenomena and it is therefore important to consider gross performance alongside subsidiary components shown to decline with fatigue.

The way strength is utilised can be important in determining performance and changes to technique may counterbalance the effect of fatigue (Byrne & Eston, 2002). With or without a measureable change in performance, the state of fatigue could influence exercise efficiency, co-ordination and injury. Holistic management of athlete fatigue and recovery therefore requires iterative deconstruction and reconstruction of performance indices between systemic and functional levels.

Sports science and medicine practice should consider high performance trained athletes differently to recreational or untrained athletes. There is a typically larger physiological response following unaccustomed activity, and the 'repeated bout effect' describes the protective or dampened response that may be observed following as little as a single previous exposure to a similar exercise bout (McHugh, 2003; Newham, Jones & Clarkson, 1987; Sacco & Jones, 1992). Resting serum CK levels can be expected up to twice as high in athletes versus non-athletes (Mougios, 2007) and post-exercise increases in CK differ with trained and untrained subjects (Brancaccio, Maffulli & Limongelli, 2007). Training influences jump characteristics and peak performance measures (Cormie, McBride & McCaulley, 2009) and attenuates the post-exercise leukocytosis (Blannin, Chatwin, Cave & Gleeson, 1996). It is therefore likely that recovery characteristics and time-course are also training-history specific.

Particularly in trained athletes, immune system recovery between training and competition could therefore be an important consideration. While short bouts of exercise boost the immune system, intense exercise can impair some aspects of immune function (Gleeson, 2007), and prolonged exercise and a high training volume also increases the risk of upper respiratory tract infections (Nieman et al., 1994). Exercise results in an acute leukocytosis (McCarthy & Dale, 1988) which should begin its return to normal immediately post exercise,

but can continue to increase during recovery from particularly intense exercise (McCarthy et al., 1992).

The complexity of the post-exercise response and contributory factors to the state of fatigue make it necessary to consider recovery at both systemic and holistic levels. Fatigue mechanisms are well described and result in undesirable decrements in athletic performance on multiple levels, including deterioration from optimal muscle activation capacity and less efficient movement. However, deciphering the integrative physiology alongside what constitutes “meaningful change” for an athlete is challenging and the direct implications on athletic performance are difficult to measure. Nevertheless, the integrated nature of fatigue confers the necessity of an integrated, multi-systemic, constructivist approach to recovery.

2.2.3 Potential mechanisms and effects of water immersion on athlete recovery

There is a substantial body of evidence describing the physiological effects of water immersion and water immersion duration, depth and temperature are important in predicting potential effects. Hydrostatic pressure of water immersion induces a cascade of physiological effects largely defined by immersion depth and duration (Pendergast & Lundgren, 2009). These effects are independent of water temperature therefore apply to immersion in cold, thermo-neutral and warm water. In addition to hydrostatic pressure mechanisms, cold and warm water stimulate cutaneous thermo-receptors launching a cascade of temperature-dependent effects (Peiffer, Abbiss, Watson, Nosaka & Laursen, 2011; Wilson et al., 2007). Therefore the influence on athlete recovery is likely to be protocol-specific, and there are likely to be different effects of cold, thermo-neutral and warm water immersion.

Kuhtz-Buschbeck, Andresen, Göbel, Gilster & Stick (2010) describe normal ambient skin temperature as 30–34°C, showing a median thermo-receptor cold detection threshold of 31°C (range 27–32°C) and warm detection threshold of 34°C (range 33–36°C). These detection threshold temperatures could be considered the defining boundaries of cold and warm water respectively. Minimal stimulation of cutaneous thermo-receptors could be anticipated in water temperatures of 30–34°C which could be considered as thermo-neutral relative to human skin temperature. According to these definitions, this review examines the potential mechanisms of effect of cold and thermo-neutral water immersion on athlete recovery.

These indicative reference ranges of cold, thermo-neutral and warm water are useful in terms of anticipating cutaneous thermo-receptor stimulation and physiological responses. However, references to ‘cold’ and ‘warm’ water immersion in athlete recovery are applied in relative terms throughout the literature. A ‘cold-cool’ spectrum is typically differentiated from a relatively ‘warmer’ spectrum and the terminology ‘warm’, ‘tepid’ or ‘thermo-neutral’ commonly refers to water temperatures in the range 25–38°C (Refer Table 2.1). Water temperatures above this spectrum could be further differentiated as ‘hot’, the physiological response to which is beyond the scope of this project. To this end, this project refers to a comparison between cold and warm water immersion, which could equally have been described as a comparison between cold and thermo-neutral water immersion.

2.2.3.1 Response to water immersion – hydrostatic pressure-dependent mechanisms and potential effects on athlete recovery

Independent to temperature, hydrostatic pressure of water immersion induces a peripheral to central blood volume shift and reduces the pressure-gradient regulated fluid transfusion from extravascular compartments to the circulatory system, increasing stroke volume and cardiac output (O'Hare et al., 1985; Pendergast & Lundgren, 2009). This transient increase in central blood volume and blood pressure induces cardio-endocrine-renal changes, including diuresis, to regulate plasma volume, peripheral resistance and blood pressure (Pendergast & Lundgren, 2009). A reactive reduction in sympathetic nerve activity causes bradycardia with a decreased cardiac output, altered arteriolar resistance with selective tissue hyper-perfusion (Pendergast & Lundgren, 2009). Increased muscular perfusion following water immersion stabilises sympathetic tone (Boussuges et al., 2009). Thus, post exercise water immersion could be considered to stabilise the nervous and circulatory systems and maximise the circulatory-perfusion ratio, which is desirable in facilitating recovery to a pre-exercise state.

Although some studies have shown no difference in circulating catecholamines (Epstein, Johnson & DeNunzio, 1983), the balance of evidence suggests sympathoadrenal activity is reduced following thermoneutral water immersion (Connelly et al., 1990; Norsk, Bonde-Peterson & Christensen, 1990). This could decrease arousal and promote relaxation during recovery, assisting the management of athlete arousal between training and competition bouts.

Although it is less clear how long cardio-endocrine-renal changes would be sustained post-immersion, Pendergast & Lundgren (2009) suggest that increased stroke volume and cardiac output persist for up to 6 hours following head out immersion. This is a conceivably advantageous circulatory condition to perfuse exercise-damaged tissues and maximise metabolic exchange to facilitate recovery in the initial post-exercise hours.

Hydrostatic pressure combined with increased central blood volume can also reduce vital capacity by loading the chest wall and increasing the work of breathing (Pendergast & Lundgren, 2009). However, the associated increased blood flow to respiratory muscles and the lungs improves the ventilation-perfusion gradient (Pendergast & Lundgren, 2009), a provision for maximal gas exchange which seems advantageous for recovery.

Although the circulatory and endocrine effects of water immersion are reasonably established and accepted, the time and immersion depth profiles of these effects is not absolutely defined. Sound evidence describes the effects of head out immersion, although much original research illuminating the precise effects of water immersion is conducted in the context of deep water diving, and necessarily details the influence of breath holding and hydrostatic pressure at greater depths and longer timeframes (Lindholm & Lundgren, 2009; Marabotti, Scalziniz, Cialoni, Passera, L'Abbate & Bedini, 2009) than typically used in athlete recovery. More pronounced effects of hydrostatic pressure have been observed with progressively increasing depth of immersion (Gabrielsen, Johansen & Norsk, 1993; Marabotti et al., 2009). Marabotti et al., (2009) observed no changes in echocardiography following head out immersion, with cardiac output and cardiac deceleration time changes only initiated at 5 metres' depth with breath hold.

Following one hour complete water immersion, Boussuges et al., (2009) observed decreased stroke volume and cardiac output, which was attributed to the decreased plasma volume rather than an alteration in cardiac contractility; and increased cardiac preload with neuro-endocrine alterations in blood volume regulation after 6 hours (which persisted for 16 hours). Increased splanchnic and renal perfusion contribute to a significant diuresis (Epstein et al., 1983), therefore sustained immersion in athletes requires conjunctive hydration and nutrition recovery strategies.

2.2.3.2 Additional temperature-dependent mechanisms and potential effects of cold water immersion on athlete recovery

Further to hydrostatic pressure, cold water temperature stimulates cutaneous thermoreceptors inducing an additional cascade of temperature dependent mechanisms and potential effects on athlete recovery. There is no evidence to suggest the effects of non-prolonged thermo-neutral water immersion would be detrimental to athlete recovery. However, interpreting whether the effects of cold water immersion would be beneficial or detrimental to athlete recovery is more complex.

While stabilised sympathetic tone follows water immersion (Boussuges et al., 2009), cold water immersion, particularly of the face, can increase sympathetic nervous system activity (Lindholm & Lundgren, 2009; Marabotti et al., 2009) which leads to accumulating athlete fatigue when prolonged (Reilly & Ekblom, 2005). However facial immersion is not common recovery practice, and circulatory changes of hypertension-induced sympathetic activity, resultant peripheral vasoconstriction, vagally induced bradycardia and decreased cardiac output are augmented by hypoxia and cooling (Lindholm & Lundgren, 2009). This could facilitate relaxation and stabilise sympathetic activation to a resting state.

Peripheral blood flow, muscular perfusion and maximal cardiac output are reduced by cold water immersion, which reduces maximal exercise capacity but does not affect resting cardiac output (Pendergast & Lundgren, 2009). Cold water immersion therefore should not be detrimental to cardiac output-influenced recovery at rest. Reduced muscular perfusion and cold-induced vasoconstriction could curb extravasation to damaged tissues, which could counterbalance consequences of mechanical disruption to sarcomere myofilaments, and calcium homeostasis across cellular membranes (Armstrong, 1990; Kendall & Eston, 2002). Vasoconstriction could attenuate the post exercise inflammatory response, reduce tissue metabolism and consequently reduced secondary hypoxic cellular damage (MacAuley, 2001).

Inversely, advantageous circulatory conditions to perfuse exercise-damaged tissues and maximise metabolic exchange to facilitate recovery may be more desirable. Warm application could enhance recovery through decreased muscle spasm, increased cellular metabolism and vasodilation, in turn increasing tissue perfusion and reduce secondary hypoxic damage (MacAuley, 2001).

Homeostasis relies on afferent feedback from peripheral physiological and neural systems (Noakes, St Clair Gibson & Lambert, 2005), and cold water immersion could impair afferent input, efferent responses, reaction time and alter neuromuscular recruitment. Decreased

temperature can affect neural cell membrane calcium and sodium transportation (Algaflly & George, 2007), prolonging muscle action potentials (Evans et al., 1995), slowing nerve conduction velocity (Algaflly & George, 2007) and depressing the myostatic reflex (Cross et al., 1996). This could manifest as slowed reaction time and performance decrements, particularly in neurally demanding skills which require reaction and strength in a short amount of time. Cooling has also been shown to increase muscle stiffness (Evans et al., 1995) and reduce force production (Cross et al., 1996).

The timeframe over which temperature change occurs is important when planning interventions. Full body cold water immersion is most effective in achieving whole body cooling (Casa, McDermott, Lee, Yeargin, Armstrong & Maresh, 2007) and enables simultaneous treatment to multiple body segments. However, animal studies have shown varied findings with regard to the ideal cooling temperature, with a likely optimal cooling to 10-15°C for reducing metabolism without increasing cell damage (via reflex vasodilation) (MacAuley, 2001). In human studies, and applied practice, it is difficult to monitor tissue temperature with this precision. Although there is a cooling gradient over time it is not linear: the balance of evidence suggests that most tissue cooling occurs in the first 10 minutes of cold application, continuing marginally up to 20 minutes (MacAuley, 2001). This suggests that 10-20 minutes of cold water immersion would induce temperature dependent changes.

2.2.3.3 Response to 5 minutes of water immersion – potential mechanisms and effects on athlete recovery

Although the magnitude of potential effects is defined by a gradient over time, there is strong evidence advocating the hydrostatic pressure induced cascade (Pendergast & Lundgren, 2009) and thermo-receptor induced cascade (Peiffer et al., 2010) are initiated immediately upon immersion. Potential advantages to athlete recovery could therefore be realised with short immersion times. Current practice commonly utilises water immersion durations of five minutes or less (Peterson, 2006; Sellwood et al., 2007; Snelling, 2006) which enables application during half-time breaks (Peiffer et al., 2010) and is a cold duration realistically tolerable to athletes (Bleakley & Davidson, 2010). It is therefore important to distinguish the mechanisms and effects which would be expected following shorter immersion times. Evidence indicates that 5 minutes of cold water immersion provokes significant circulatory changes which could influence athlete recovery.

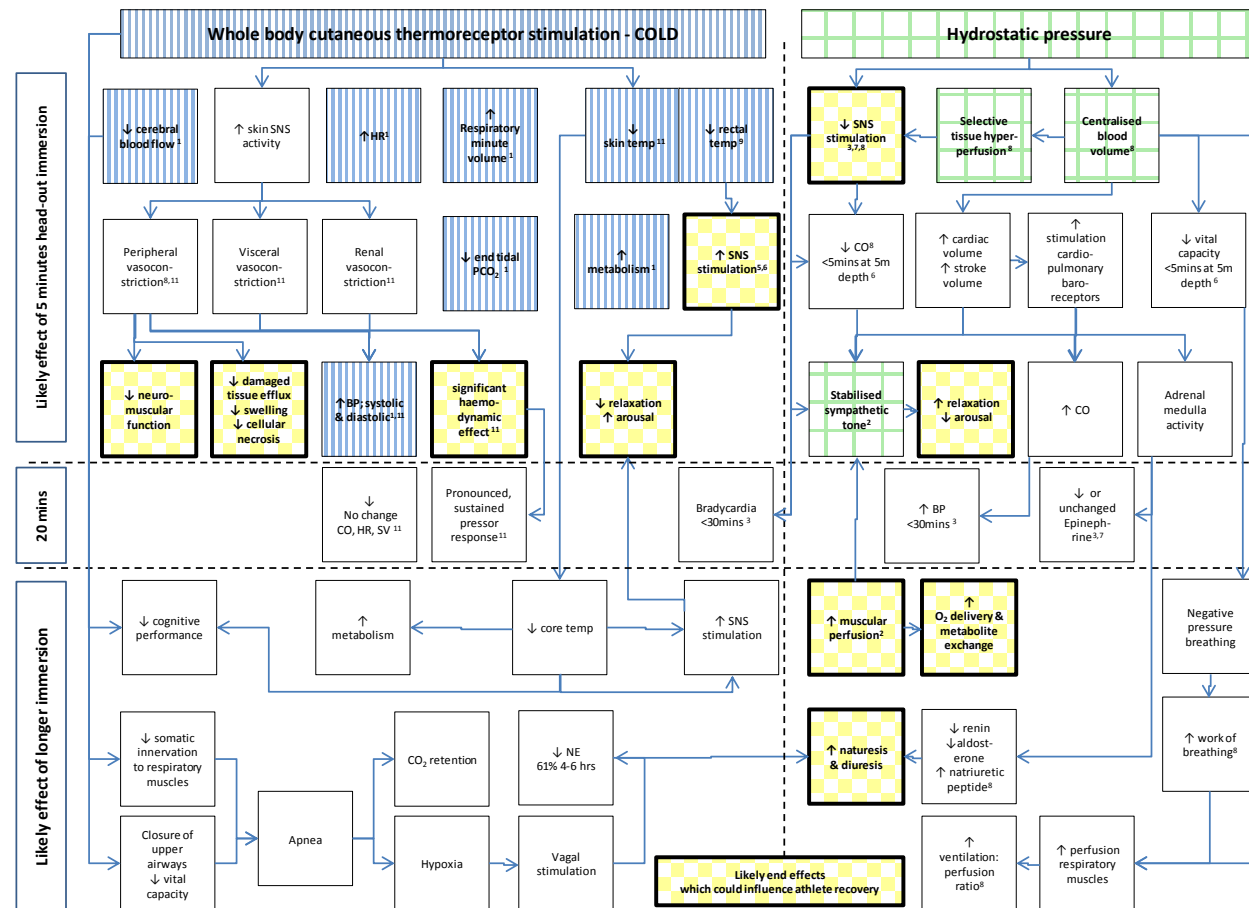
In a recent review paper, Pendergast & Lundgren (2009) report the initial cardiovascular changes due to hydrostatic pressure as “immediate” in head-out immersion in thermo-neutral water. On immersion, negative transthoracic pressure and negative pressure breathing are established and central blood volume increases within six heart beats (Datta & Tipton, 2006). The balance of evidence suggests the initial effects and further systemic responses are likely to be proportional to immersion duration (Figure 2.3).

Cold does not augment the blood volume shift (Datta & Tipton, 2006) but does augment many elements of the sympathetic nervous system response to water immersion (Lindholm & Lundgren, 2009; Marabotti et al., 2009). Although reduced muscle temperature does not occur

within 5 minutes (Higgins & Kamanski, 1998; Myrer Draper & Durrant, 1994; Myrer, Measom, Durrant & Fellingham, 1997), a rapid (4°C) drop in skin temperature (Peiffer et al., 2008), reduced subcutaneous temperature (Myrer et al., 1997) reduced rectal temperature (Peiffer et al., 2010) and immediate onset of peripheral vasoconstriction (Peiffer et al., 2008; Wilson et al., 2007) have been demonstrated. Wilson et al., (2007) concluded that 5 minutes of 14°C cutaneous thermo-receptor stimulation induced significant haemodynamic effects and a sustained pressor response.

A recent systemic review studied the biochemical and physiological effects of 5 minutes or less head-out cold water immersion (Bleakley & Davidson, 2010). Sixteen studies with large heterogeneity and small sample size were included, describing likely increases in heart rate, blood pressure, respiratory minute volume, metabolism, peripheral catecholamine concentration and oxidative stress; and decreases in end tidal carbon dioxide partial pressure and cerebral blood flow. Furthermore an immediate “cold shock” is initiated by reduced skin temperature, characterised by an inspiratory gasp, hypertension and hyperventilation (Datta & Tipton, 2006). Although often associated with extreme cold and temperature gradients, athletes could experience a similar respiratory response to cold water immersion. The end effect of these phenomena on athletic performance is unknown.

Although physiological effects of water immersion are well established, further delineation of the time-response gradient and effects on neuromuscular performance is required to inform water immersion practice in athlete recovery. Particularly, rationalisation of shorter immersion times in the order of 5 minutes’ duration is required. Both cold and warm water immersion could be theoretically desirable, although some responses to cold water immersion could be detrimental to athletic performance. Figure 2.3 illustrates the potential physiological mechanisms and effects of water immersion over time.



Developed based on information sources: 1. Bleakley & Davidson (2010); 2. Boussuges et al., (2009); 3. Connelly et al., (1990); 4. Ingram et al., (2009); 5. Lindholm & Lundgren (2009); 6. Marabotti et al., (2009); 7. Norsk et al., (1990); 8. Pendergast & Lundgren (2009); 9. Peiffer et al., (2010); 10. Vaile, Gill & Blazevich (2007); 11. Wilson et al., (2007)

Figure 2.3 Potential physiological effects of water immersion: mechanisms of hydrostatic pressure and whole body cutaneous thermo-receptor stimulation (cold) and an indicative time-response gradient. Potential responses to water immersion are duration and temperature dependent. An indicative time-response gradient is shown. Independent of temperature, hydrostatic pressure induces a cascade of physiological effects. In addition, cold water immersion launches a temperature- response cascade. Therefore the influence on athlete recovery is likely to be protocol-specific, and there are likely to be additional effects of cold compared to thermo-neutral water immersion. Likely end effects which could influence athlete recovery are shown in bold-box.

2.2.3.4 Outcome measures as indicators of recovery and mechanisms

Circulating markers of muscle damage

Myofibre proteins such as CK and myoglobin are accepted indicators of muscle damage following exercise (Rodenburg et al., 1993). Although used widely as an index of muscle damage, overexertion and adaptation (Mougios, 2007) the exact mechanism responsible for elevated CK activity post-exercise is unclear. Raised serum CK activity could be attributed to mechanical damage of skeletal muscle sarcomeres or metabolic fatigue which increases membrane permeability and cellular efflux of CK (Brancaccio et al., 2007; Kendall & Eston, 2002). Generally, CK release from skeletal muscle is considered a poor indicator of muscle damage, but a good indicator of muscle membrane and sarcolemma stability and disruption (Tiidus, 2005). This evidence considered, elevated CK is an indicator of altered post-exercise physiological state and water immersion during recovery could have the desired outcome of facilitating a return to pre-exercise levels. Mechanisms of effect could include restoration of membrane stability as well as curtailing muscle damage and the secondary inflammatory response.

Although the optimal 'distribution' of leukocytes for immune function and recovery is unknown, the haemodynamic effects of water immersion could influence leukocyte distribution. The balance of evidence attributes much of the leukocyte demargination to increased heart rate and cardiac output and therefore higher mechanical shear forces post-exercise (Blannin, 2006) which could be stabilised following water immersion. It has been suggested that leukocyte remargination is focussed in the spleen (Blannin, 2006) and could therefore be augmented by increased central blood volume following water immersion.

Neutrophils could cause secondary damage through phagocytosis of healthy as well as damaged cells and debris (St. Pierre Schneider & Tiidus, 2007; Tiidus, 2005) and neutrophil-produced free radicals could damage leukocyte DNA and create oxidative stress if produced in excess (Peake & Suzuki, 2004). Temperature-mediated attenuation of the post-exercise neutrophilia could curtail secondary damage, however it is unclear whether this would be desirable as it also forms the initial stages of repair and defence to invading microorganisms (Braun & von Duvillard, 2004; Lagranha et al., 2008).

Neuromuscular function and performance

Water immersion could facilitate the recovery of muscle function via hydrostatic pressure-mechanisms restoring the cellular environment to pre-exercise conditions. This conceivably favours optimal neuromuscular activation and motor-unit contractile capacity. However, cryotherapy is likely to have inhibitory effects on muscle function for up to 30 minutes (MacAuley, 2001), and the temperature effect of cold water immersion could be counterproductive. These mechanisms could manifest as altered muscular force production and functional performance, which could be measured with indices of maximal torque, functional performance and neuromuscular recruitment patterns.

2.2.4 Interventions to facilitate recovery

Active recovery

There is consensus that engaging in active exercise to facilitate recovery is better than passive recovery or rest. Active recovery has been reported to facilitate lactate removal, a smoother decline in body temperature, dampened nervous system activity and arousal levels (Reilly & Ekblom, 2005; Barnett, 2006). Low intensity exercise has been associated with more effective blood lactate removal than massage (Hemmings, 2001; Monodero & Donne, 2000), decreased muscle soreness and improved performance in vertical jump, broad jump and sprint fatigue tests (Reilly & Rigby, 2002), and enhanced psychological recovery in rugby players (Suzuki, Umeda, Nakaji, Shimoyama, Machico & Sugawara, 2004).

The importance of lactate must be discerningly interpreted, as although lactate elimination has been used as an indicator of recovery (Morton, 2007), acidosis has a questionable effect on contractile proteins at body temperature (Pate, Bhimani, Franks-Skiba & Cooke, 1995). It is also suggested that lactate could contribute to energy production and facilitate performance (Allen & Westerblad, 2004; Cairns, 2006; Gaesser & Brooks, 1984). There is much scope to refine the ideal 'activity' during active recovery as recovery should not add to the overall work or physical stress of the athlete. Active recovery could impair glycogen resynthesis compared to passive recovery (Choi, Cole, Goodpaster, Fink & Costill, 1994; Fairchild, Armstrong, Rao, Lui, Lawrence & Fournier, 2003), further eccentric exercise can increase post exercise muscle soreness (Nosaka & Newton, 2002; Takahashi et al., 2006) and athletes often poorly judge the 'low intensity' parameter of recovery exercise (Brukner & Khan, 2007).

Although advocating the consensus for active recovery, Barnett (2006), in a comprehensive critical review of literature commented that "there is no substantial scientific evidence to support the use of the recovery modalities....to enhance the between-training session recovery of elite athletes" (p782). Since publication of this review, there has been intense investigation of athlete-oriented active recovery interventions involving water immersion (Bailey et al., 2007; Banfi, Melegati & Valentini, 2007; Ingram et al., 2009; Peiffer et al., 2008; Peiffer et al., 2010; Rowsell et al., 2009; Sellwood et al., 2007; Vaile et al., 2008), which provides for low intensity active recovery with minimal eccentric muscular activity.

Water immersion recovery interventions

Commonly utilised water-immersion recovery strategies can be described according to the water temperature, depth, immersion duration and activity undertaken during immersion. Each of these descriptors could affect recovery differently, making general conclusions regarding the efficacy of water immersion recovery difficult. Given the specificity of the post-exercise response, evaluation of water immersion recovery interventions should also be exercise, population, outcome measure and immersion protocol specific. However, a literature review evaluating the effects of water immersion on athlete recovery would be incomplete without firstly considering the broader evidence base prior to narrowing the specificity of

athlete profiles and exercise scenarios. Table 1.1 summarises the publications with the most relevant findings to this project.

Takahashi et al., (2006) suggest that athlete recovery from downhill running could be maximised by exercise in water at 29°C on the day of and day post maximal exercise, showing quicker recovery of muscle power, stiffness and soreness following aqua exercise. Byrne & Easton (2002) and Takahashi et al., (2006) observed similar patterns of post-exercise CK elevation one hour to 3 days post exercise with a peak at 1 day, and strength reductions persisting for 4 days. Recovery of muscle function was independent of CK; although CK represents muscle damage further measures are needed to evaluate recovery of neuromuscular performance.

Eston & Peters (1999) also showed a significant decrease in CK during a regime of 15 minutes immersion at 15°C, immediately following and every 12 hours after eccentric exercise. CK levels peaked in the control group at 2-3 days, a similar pattern observed by Takahashi et al., (2006) and Bryne & Eston (2002). However, in this study it appears that the cool water treatment attenuated the CK peak, supporting theory that immersion in colder temperatures is more effective than warm in reducing post exercise muscle damage.

Hornery, Papalia, Mujika & Hahn (2005) found that halftime cooling resulted in greater aerobic performance in cyclists, along with a dramatic placebo effect indicated by psychological assessment. Heart rate, blood lactate concentration, rate of perceived exertion, and subjective rating of feelings and emotions differed from a control group while sweat loss, core and mean skin temperature did not differ significantly. This further supports the post-positivist evaluation of the effects of intense exercise, recognising the value of both physiological phenomena and social constructs in athletic performance.

Despite these observations and rationale grounded in established theory of cryotherapy, counterproductive effects of cold water immersion have been proposed, which means its application between exercise sessions must be carefully considered. Slowed nerve conduction velocity due to cooling has analgesic benefits, but a depressive effect on the myostatic reflex and force production (Cross et al., 1996), prolongs muscle action potentials and increases stiffness (Evans et al., 1995). Lowered agility time scores have been observed following cold application (Evans et al., 1995) and declines in vertical jump and shuttle run scores in footballers following a 20 minute 13°C lower leg ice application have been demonstrated (Cross et al., 1996). This suggests that cryotherapy can have detrimental effects on performance, possibly through a mechanism of attenuating neural function. This emphasises the need to further explore the neuromuscular effects of cold water immersion.

The inflammatory response to training overload is important in stimulating tissue load adaptation and developing resistance to subsequent exercise induced muscle damage (McArdle et al., 2007), and it is debated whether cold water immersion attenuates hyperthermia and inflammatory dependent training adaptations. Although the rate of post-exercise glycogen synthesis and the role of inflammation in training adaptations have not been conclusively investigated (Barnett, 2006), Snelling (2006) advises use of ice baths to reduce inflammation post competition, but not post training. Yamane et al., (2006) concluded that exercise hyperthermia dependent training adaptation is attenuated by sustained post exercise

cooling, however subjects were non-athletes. This is a criticism of many studies as the response to both intense exercise and unfamiliar recovery interventions differs in trained and untrained individuals (Branciaccio et al., 2007; McArdle et al., 2007).

Alternating immersion in hot-cold water could speed recovery by increasing the peripheral circulation, stimulating the central nervous system, enhancing blood flow to the fatigued muscle, and reducing post exercise oedema (Calder, 1996). Cochrane (2004) identified alternating vasoconstriction and vasodilatation as a possible mechanism of slowing metabolism, improving metabolite removal, and repairing exercise induced muscle damage. Although the physiological effects of hot-cold water contrast on tissue are well documented, a systematic review by Cochrane (2004) found few studies focussed on hot-cold water immersion for post exercise recovery and its influence on improved recuperation. Since this review further research has confounded this speculation, informing current practice to some extent but with inherent design limitations.

Using untrained subjects, Sellwood et al., (2007) found no significant difference in the efficacy of a contrast protocol compared to tepid water immersion on prevention of DOMS, following seated leg extension in a randomised double-blind controlled trial. There was no control group, so it is unclear whether both these conditions would be different to passive rest. It is also unclear whether these findings would apply to trained athletes following intense exercise and to measures of recovery other than DOMS.

Eighty four hours following a rugby match, Gill et al., (2006) observed an 84% recovery of plasma CK following contrast immersion of 1 minute cold : 2 minutes hot for 9 minutes, compared with a 39% recovery in players who sat for a 9 minute passive recovery. CK was only measured immediately post match, and at 36 and 84 hours, leaving a gap in measurement between 24-48 hours, a time frame which findings of other studies have inferred to be the most crucial (Takahashi et al., 2006; Byrne & Easton, 2002). This suggests evaluation of the timeframe inside 24-36 hours when most athletes would participate in further training and or competition is worthwhile.

Vaile, Gill & Blazeovich (2007) observed a faster restoration of explosive performance and strength with contrast baths compared to passive recovery and Hamlin (2007) indicated a sustained lower heart rate following a contrast versus active recovery regime, although observed trivial difference in repeated sprint performance. The links between these varied scientific observations and the impact on athletic performance require further elucidation.

In a review article of water immersion recovery strategies, Wilcock et al., (2006) suggested “cool to thermo-neutral temperatures may provide the best range for recovery” (p748), although determined much evidence of water immersion having a positive influence on performance to be anecdotal. Further research is needed to establish the benefits to athletes, including specification of appropriate activity undertaken while immersed, the ideal temperature and immersion timeframes and theory to support these recommendations.

Several recent studies have utilised exercise protocols similar to the demands of intense exercise, a spectrum rather than isolated outcome measures, and recovery protocols similar to current practice. The combined consideration of these studies enables more specific

identification of strengths and weaknesses of the current evidence base, although the variety in experimental protocol and outcome measures renders meaningful consolidation of the findings and application to practice challenging. Clarity is better preserved by interpreting these studies individually, with further research necessary to reproduce the observations and facilitate generalisation to the athlete community.

Bailey et al., (2007) observed that 10 minutes of water immersion to the level of the anterior superior iliac spine (ASIS) at 10°C facilitated the recovery of isometric knee flexion strength at 24 and 48 hours post-Loughborough intermittent shuttle test (LIST). This study involved habitual exercisers, unfamiliar to the LIST. The applicability of these results to the athletic population could be substantiated with the exploration of the response in trained, familiarised subjects. Furthermore, the question remains whether the beneficial effect on knee flexion recovery would be observed following shorter immersion times and / or warm water immersion.

Ingram et al., (2009) compared 15 minute protocols of cold water immersion at 10°C to the umbilicus, with hot/cold contrast immersion and passive rest, also at 24 and 48 hours post exercise. Team sport athletes followed an exercise-fatigue protocol comparable to the LIST demands. No significant effect of intervention was observed in CK, c-reactive protein, knee flexion or extension strength, although it was reported that strength losses observed at 48 hours following contrast and passive recovery were not observed following cold water immersion. Repeated sprint performance showed a more rapid return to baseline following cold water immersion. At 24 hours post exercise, muscle soreness ratings were significantly lowest after cold, and significantly lower following contrast immersion than passive recovery. These results strongly suggest that water immersion, particularly cold, is advantageous to recovery, although further research with similar observations or more robust statistical findings would render this more compelling.

Peiffer et al., (2008) showed greater decrements in knee extension isometric maximum voluntary contraction (iMVC) (at 60°) and iMVC with superimposed electrical stimulation following 20 minutes of cold water immersion at 14°C compared with passive control, although measurement were only recorded up to 90 minutes post exercise. Femoral vein diameter was also significantly decreased (by 9%) post exercise, attributed to decreased plasma volume, and further significantly decreased by cold water immersion (-12%), attributed to vasoconstriction. The authors suggest this circulatory-reducing effect could have a negative effect on recovering muscles. Although immediate reduction in skin temperature was observed which could initiate vasoconstriction, it remains indeterminate whether reduced muscular circulation would result following shorter immersion times.

Vaile et al., (2008) showed 14 minutes of head-out cold (15°C) water immersion and contrast immersion was beneficial to loaded squat jump performance and isometric squat force recovery; and hot water immersion (38°C) to isometric squat force recovery. This study emphasised muscle loading and followed an eccentric leg press protocol, which also suggests effects could be movement-pattern specific. Decreased perceived pain following contrast water immersion compared to passive at 24, 48 and 72 hours was reported; decreased CK following cold and hot water immersion compared to passive and no change in myoglobin

were observed. This study included multiple statistical comparisons, and did not offer an explanation of statistically significant findings at non-chronological time points.

Rowell, Coutts, Treaburn & Hill-Hass (2009) also evaluated a broad spectrum of outcome measures in an attempt to build a picture of overall recovery in practice-simulated conditions. Physical performance tests and perception of fatigue/recovery during a four day simulated soccer tournament were evaluated. The athletes undertook post match 5x60sec water immersion at either 10°C (n=6) or 34°C (n=7), finding less muscle soreness and general fatigue following 10°C water immersion and no difference in any physiological measures including countermovement jump and serum CK. There was no control group and measures were recorded immediately and 22 hours post exercise, meaning an effect inside these time-points or compared to control could have been missed. The simulated tournament had the strengths of replicating competition but could not afford the rigour of controlled exercise conditions in a cross over design. The test interventions of 5 alternating exposures of 60secs water immersion: 60secs resting on a chair are further examples of the variety of protocol used in current practice, making it difficult to generalise conclusions.

Most of these studies utilised water immersion between 10 and 20 minutes: there is considerable disparity between the evidence base of studies evaluating water immersion for sustained periods and clinical practice, which commonly utilises shorter lengths of immersion (Peterson, 2006; Sellwood et al., 2007; Snelling, 2006). Immersion times in the order of 5 minutes are logistically more feasible between successive exercise bouts, such as during half-time breaks, and cold exposure time more realistically tolerable to athletes (Bleakley & Davidson, 2010).

The only other study found to evaluate the effects of water immersion of 5 minutes duration was published subsequent to the conduct of this project. Peiffer et al., (2010) showed 5 minutes cold immersion at 14°C decreased rectal temperature and maintained cycling endurance performance in a subsequent time trial in the heat. Core temperature stability is particularly important to athletes exercising in the heat, although further research is necessary to explore the benefits to athletic performance in moderate ambience or subsequent exercise bouts separated by greater lengths of time, and the effects of this protocol on other recovery indices.

There are anecdotal reports that water immersion recovery is justified, however the mechanisms of effect and the ideal protocol for use in athlete recovery remain equivocal. The effects of water immersion on neuromuscular performance require further scrutiny alongside their relationship with the post-exercise muscle damage and inflammatory responses. Consistency between studies' design protocol and observations would assist the delineation of clinical equipoise and more confidently inform clinical practice.

Table 2.1 Water immersion in athlete recovery: summary of key publications informing this project

Subsequent to a comprehensive literature review of the post-exercise response, potential effects of water immersion on athlete recovery and interventions to facilitate recovery, a summary of key publications informing this project is presented. Review publications, including the type of review, are differentiated from publications with experimental designs. Of the experimental designs: Firstly, studies most closely replicating demands on athletes and recovery from intense exercise were identified. Secondly, studies describing alternate research and exercise protocols but with findings relevant to informing this project were identified. Key descriptors of study design, methods and outcomes are indicated.

Publication Type	Author	Topic	Detail of review	Key conclusions
Review	Barnett (2006)	Recovery modalities between training sessions in elite athletes	Recovery modalities of massage, active recovery, cryotherapy, CWT, hyperbaric oxygen therapy, NSAIDs, compression garments, stretching, electromyostimulation and combination modalities.	There is no scientific evidence to support recovery modalities. The body of evidence does not reflect the between-training session circumstances of athlete recovery, and particularly involves untrained subjects and large volumes of unfamiliar eccentric exercise
Systematic review	Bleakley & Davison (2010)	Biochemical & physiological rationale for using cold water immersion in sports recovery	Physiological & biochemical effects of CWI <150C, ≤ 5minutes	Scientific rationale of CWI remains unclear. CWI is associated with ↑HR, ↑BP, ↑respiratory minute volume, ↑metabolism, ↓end tidal CO ₂ pa, ↓cerebral blood flow; ↑peripheral catecholamine concentration, oxidative stress & free radical formation. Acclimatisation is likely to attenuate these responses.
Literature review	Cochrane (2004)	Alternating hot and cold water immersion for athlete recovery	Scientific rationale & mechanisms of using CWT for post exercise recovery	Anecdotal reports overwhelmingly support CWT although the physiologic effects are less known. The shunting action of vasodilation and vasoconstriction could be the mechanism of effect. More research is needed, particularly evaluating CWT post-exercise.
Review	Wilcock, Cronin & Hlng (2006)	Physiological response to water immersion in sports recovery	Physiological response during non-exercise immersion; effects of hydrostatic pressure & temperature	Much of the evidence is anecdotal and research on performance change is limited. Physiological effects of water immersion include intra-cellular-intravascular fluid shifts, ↓muscle oedema & ↑CO. Water immersion effects are temperature dependent & cool to thermoneutral temperatures may be optimal for recovery.

Publication Type	Author	Participants	Study design	Test exercise	Intervention	Exercise response observations	Changes observed	No change	Conclusion	Unanswered questions
Studies most closely replicating demands on athletes and recovery from intense exercise	Bailey, Erith, Griffin, Dowson, Brewer, Gant & Williams (2007)	Habitual exercisers, unfamiliarised (n=20)	Matched pairs	LIST	CWI 10mins 10°C to ASIS	Severe muscle soreness; Myoglobin peak at 1 hr; CK peak at 24 hours;	CWI ↓ MVC (KF) at 24 & 48 hours; CWI ↓ myoglobin peak; CWI ↓ muscle soreness at 1, 24, 48 hours;	Vertical jump height, Sprint performance, Serum (Hb, haematocrit, CK), Muscle soreness	COLD 10mins 10°C to ASIS reduces some indices of exercise induced muscle damage	Can findings be replicated following shorter immersion, in familiarised & trained athletes?
	Ingram, Dawson, Goodman, Wallman, Beilby (2009)	Team sport athletes (n=11)	Randomised cross over	80mins simulated team sport ex + 20m shuttle to exhaustion	COLD to umbilicus 15mins vs CWT vs control	CK peak at 24 hours	COLD ↑ return to baseline repeated sprint (iso leg ext & fl, cable tensiometer); COLD ↓ strength; COLD ↓ muscle soreness; CWT ↓ muscle soreness at 24	Serum (Hb, haematocrit, CK, CRP); no correlation CK muscle soreness	COLD 15mins at 10°C offers greater recovery benefits than CWT or control	Can ad hoc chronological findings be explained? Are findings reproducible?

Publication Type	Author	Participants	Study design	Test exercise	Intervention	Exercise response observations	Changes observed	No change	Conclusion	Unanswered questions
Studies most closely replicating demands on athletes and recovery from intense exercise	Peiffer, Abbiss, Nosaka, Peake & Laursen (2008)	Trained male cyclists ($n=10$)	Randomised cross-over	2x90min cycling at constant power followed by 16.1km time trial in the heat	COLD 20min 14°C vs control	MVC - 12% dec fatigue, 13% ↓ COLD - therefore peripheral not central mechanism proposed;	Neuromuscular function (KE 60deg MVIC + superimposed) - COLD ↓ iMVC & superimposed iMVC persisting 90mins; Femoral vein diameter - COLD ↓ 9% 45mins; Rectal temperature - COLD ↓ 0.5°C & sig ↓ at 50mins, sig ↓ from baseline at 70mins; Skin temperature - COLD rapid ↓ 4°C deg drop & sig ↓ from 25mins		COLD 20mins at 14°C decreases rectal temperature and neuromuscular function	Would the neuromuscular function detriment be evident following shorter immersion? Would these findings apply to other sports? At usual ambient temperatures?
	Peiffer, Abbiss, Watson, Nosaka & Laursen (2010)	trained male cyclists ($n=10$)	Counter-balanced cross over	25mins constant pace cycling at 65% VO2max followed by high intensity 4km (≈6mins) time trial in the heat	COLD 14°C 5mins	↑rectal temperature; subsequent time trial: ↑av completion time, ↑RPE	COLD ↓rectal temperature immediately following immersion & during subsequent time trial; In subsequent time trial COLD ↑cadence, ↑av power output, ↓av completion time, ↓RPE	Exercise economy (VO ₂) subsequent time trial	COLD 14°C 5mins decreased rectal temperature in hyperthermic athletes & maintained cycling endurance performance	Would these findings apply to other sports? In moderate ambient conditions? Would 5 minutes of immersion affect other recovery indices? Would these effects be meaningful in subsequent exercise bouts separated by greater lengths of time?
	Rowsell, Coutts, Reaburn & Hill-Haas (2009)	high performance soccer ($n=20$)		4 day simulated soccer tournament	COLD 10°C 5x60sec vs WARM 34°C 5x60sec		COLD ↓ leg soreness & general fatigue perception	Countermovement jump height (Vertec); 5min run + 12x20m sprint performance; CK	COLD 10°C decreases muscle soreness & fatigue, but does not effect physical performance or indices of muscle damage & inflammation	Would these results be reproducible in a cross over design & compared with a control? Were effects missed between the measurement time-points of immediately & 22 hours post exercise?
	Vaile, Halson, Gill & Dawson (2008)	strength trained males ($n=38$)	Randomised cross-over (intervention vs no intervention)	DOMS inducing leg press	COLD or WARM or CWT 14mins vs PASS	Force platform weighted squat jump & isometric squat: no post exercise change	CWT ↑ weighted squat jump at 24, 48, 72hours; COLD ↑ weighted squat jump at 48,72hours; WARM ↑ isometric squat at 24, 48, 72 hours; COLD ↓ perceived pain; CWT ↓ perceived pain at 24, 48, 72; WARM ↓ CK at 24, 72;	Thigh girth; Mb, IL-6, LDH	COLD & CWT improved recovery of isometric force, dynamic power & localised oedema compared with PASS	Would these effects following eccentric exercise also follow intense exercise? Would individual responses to COLD/WARM or CWT have influenced these results? cross over

Publication Type	Author	Participants	Study design	Test exercise	Intervention	Exercise response observations	Changes observed	No change	Conclusion	Unanswered questions
							WARM↓ CK at 48 hours			
Alternate research & exercise protocols with relevant findings	Takahashi, Ishihara & Aoki (2006)	male distance runners (n=10)	Randomised	downhill running	aqua exercise (30mins walk, jog, jump in water on 3 successive days) versus control		↓ muscle power day 1 & ↑ calf muscle soreness in control grp day 3; ↓ calf stiffness aquatic group over 4 days	CK; max leg press, flexibility, whole body reaction time (forceplate)	Aquatic exercise promotes leg muscle function recovery	
	Hornery, Papalia, Mujika & Hahn (2005)	male & female volunteers (n=14)		1 hr cycling protocol	10mins halftime cooling jacket		10min max cycle improved following cooling; Differed between cooling & control: HR, lactate, RPE, feelings & emotions	Sweat loss; core & mean skin temp; rating of thermal sensation	Psychological assessment revealed a dramatic placebo effect	
	Suzuki, Umedo, Nakaji, Machiko & Sugawara (2004)	japanese college rugby (n=15)	Randomised	Rugby match 80mins	Normal daily exercise vs additional 1 hour aquatic ex per day	Demonstrated post match muscle damage, ↓ neutrophil function, mental fatigue	↓ Profile of mood states score (POMS) in aquatic ex group	Blood biochemistry, neutrophil function; phagocytic activity & oxidative burst	Low intensity exercise had no adverse effect on physiological recovery and was beneficial to psychological recovery through enhanced relaxation	Would water immersion have similar a relaxation effect to low intensity exercise in recovery?
	Eston & Peters (1998)	females (n=15)	Randomised	8x5 maximum eccentric elbow flexion	COLD 15°C 15mins immediately post & every 12 hours for 7 sessions to exercised arm		COLD ↓CK day 2 & 3	Muscle tenderness; Isometric elbow flexion strength; upper arm circumference	COLD may reduce muscle stiffness & post-exercise damage but there is no effect on tenderness perception & strength loss	Ecc exercise; greater body immersion
	Sellwood, Brukner, Williams, Nicol & Hinman (2007)	untrained volunteers (n=40)	Randomised	5x10 seated leg extension with non-dominant leg	3x1min COLD 5°C versus TEPID 24°C			Pain & tenderness VAS; swelling (thigh circumference); SL hop for distance; max iso strength; CK	Challenge use of these practices	Ecc exercise; single leg exercise; greater body immersion
	Banfi, Melegati & Valnentinini (2007)	rugby (n=30)	Publication - letter. Study design: 3 groups	intense training session rugby	PASS versus CWT versus COLD 10mins + active versus active + COLD			Forearm interstitial CK recovery	COLD after training and active recovery stabilises CK activity	Full study requires scrutiny

Publication Type	Author	Participants	Study design	Test exercise	Intervention	Exercise response observations	Changes observed	No change	Conclusion	Unanswered questions
Alternate research & exercise protocols with relevant findings					10mins. Immersion to ASIS					
	Gill, Bevan & Cook (2006)	elite male rugby (<i>n</i> =23)	Randomised	competitive rugby match	CWT (8-10°C/40-42°C) versus compression garments versus low intensity exercise versus passive recovery		Enhanced CK clearance at 36 & 84 hours: CWT, compression garments, low intensity exercise		Low impact exercise, compression garments or CWT enhances CK clearance compared to passive recovery	Effects on indicators of recovery besides CK? Effects at post-exercise time-points between 36 and 84 hours?
	Vaile, Gill & Blazeovich (2007)	recreational athletes (<i>n</i> =13)		DOMS inducing leg press	CWT	CWT was associated with a smaller reduction and faster restoration of strength and power compared to PAS	Isometric force: CWT not ↓ below baseline measures, PASS ↓ below baseline immediately post, 4 hours & 48 hours post recovery. Jump squat peak power: PASS marginally greater ↓; Thigh volume: CWT ↓ immediately	CK; perceived pain	CK activity in top-level rugby players and can	
	Hamlin (2007)	junior representative rugby players (<i>n</i> =20)	Randomised cross over	10x40m sprints	6mins CWT (8-10°C/38°C) versus 6mins slow jogging		CWT ↓ lactate at 3mins; CWT ↓ HR	Repeated sprint performance (10x40m) trivial or unclear	CWT decreases lactate and HR but has little effect on repeated sprint performance	

2.3 Summary of strengths and weaknesses in the current knowledge base

The practice of cold and warm water immersion is commonplace in the trained athletic population however the evidence base does not sufficiently justify current practice. Current practice involves water immersion regimes varying between 1-5 minutes immersion at different temperatures, based on athlete preference and a variety of professional recommendations (Peterson, 2006; Sellwood et al., 2007; Snelling 2006). Similar theoretical principles of water immersion and cryotherapy are central to all these suggested protocols, however the parameter variations demonstrate an opportunity to refine this area of knowledge. Limitations of current research include weaknesses in study design, disparity between statistical significance and clinical benefit, speculative underlying mechanisms and the use of indirect outcome measures. Investigations have involved a range of subject populations, outcome measures and exercise parameters which have contributed to a body of varied findings, making between study comparisons difficult.

Key issues in the evidence base that make it difficult to inform water immersion practice:

1. Broad spectrum of water immersion temperatures
2. Evaluation following non-comparable exercise protocols
3. Use of untrained participants
4. Different water immersion protocols (i.e. different intervention)
5. Different outcome measures
6. Contradictory and varied findings
7. Mechanisms of effect are speculative rather than established

The body of evidence supports further investigation of the efficacy of recovery interventions involving water immersion in enhancing athlete recovery, particularly in justifying shorter immersion times and varied temperatures used in current practice. There is rationale to suggest that current practice is beneficial, although potential counterproductive intervention effects are uncertain, such as increasing energy expenditure, adding to fatigue or attenuating training adaptations. Impairment of training adaptations following sustained cooling protocols have been reasonably suggested but not convincingly substantiated. Evidence suggests that cold water immersion interventions of shorter duration entailing non-eccentric exercise are most likely to achieve a balance of these benefits whilst avoiding counterproductive considerations. It is unknown whether immersions of shorter duration would attenuate inflammation, but allow the normal adaptation process and avoid potential detrimental effects.

Much evidence has evaluated recovery interventions following eccentric exercise, and further exploration of the efficacy of water immersion following intense intermittent exercise which replicates the demands of team sports would add to the evidence base. Furthermore, even though it is well established that responses to exercise and recovery adapt with training, many studies have used untrained subjects rendering the validity of extrapolating these outcomes to the target athlete population unclear. Evaluation of the trained population familiar with intense exercise is necessary to determine the efficacy of recovery interventions in high performance athletes.

There are many outcome measures representative of overall athlete recovery. The spectra of physiological, neuromuscular and psychological outcomes following water immersion recovery interventions in the order of 5 minutes have not been convincingly established. Since short periods of cold water immersion do not alter intramuscular temperature (Higgins & Kamanski, 1998; Myrer et al., 1994; Myrer et al., 1997), mechanisms other than this should be considered to explain observations in clinical studies with shorter immersion times. Although the processes of cellular and inflammatory recovery from intense exercise seem reasonably understood, the correlation between physiological outcomes measures and a competitive performance advantage is unclear (Siegler, Bell-Wilson, Mermier, Faria & Robergs, 2006; Barnett, 2006).

Despite much evidence describing immune response to exercise, there is scant evidence evaluating the effect of recovery interventions regulating the inflammatory and immune responses. There is strong evidence that carbohydrate ingestion can attenuate post exercise immunosuppression (Braun & von Duvillard, 2004; Venkatraman & Pendergast, 2002) and it is reasonable to evaluate whether other recovery interventions, such as water immersion, could have a similar effect.

Most studies have assumed a positivist epistemology, with theory grounded in the empirical data of previous literature and scientific observation. Although the science of physiology is appropriately investigated in this paradigm, variations and inconsistencies between study findings could be reflective of a constructivist reality surrounding athletic performance, whereby physiological and social phenomenon interact to shape a performance outcome. The nature of these interactions has not been specifically investigated.

2.4 Chapter summary

With anecdotal support from the sport science and medicine community, cold and warm water immersion are commonplace interventions aiming to facilitate athlete recovery. However, the evidence base does not sufficiently replicate context-specific demands on athletes or justify the variety of current practice protocols. There is a need to further evaluate efficacy based on the spectrum of empirical and constructivist outcome measures, and their inter-relationship, which influence athletic performance. To inform practice in high performance sport, continued focus on trained participants in specific training and competition context is necessary.

Chapter 3 STUDY 1: METHOD DEVELOPMENT

3.1 Introduction

Any effect size of water immersion on athlete recovery is likely to be small, and slowed neural conduction was a proposed mechanism of effect. Methodologies are therefore needed to measure neuromuscular activation at the greatest level of detail and enable evaluation of mechanism as well as effect.

This section describes a measurement approach that was piloted for use in the evaluation of water immersion efficacy, but was ultimately not found to be sufficiently reliable to be used in the evaluation of an intervention. The intention was to evaluate neuromuscular recruitment patterns using surface electromyography (sEMG) and functional wavelet analysis, which offers the possibility of differentiating fast and slow twitch motor unit activation.

3.2 EMG-wavelet analysis in practice: Repeatability of measuring the relative recruitment of fast and slow twitch motor units during isometric MVC in human lower limb muscles

3.2.1 Introduction

In practice, surface electromyography (sEMG) is an accepted outcome measure provided the electrodes remain in situ throughout the testing period. Potential measurement error arises if the electrodes are removed and replaced, as it cannot be guaranteed that repeat sampling occurs from the same motor unit. It was not feasible to preserve the electrode placement during the study protocol of maximal exercise, water immersion, and repeated measures on different days. Replicating electrode position as accurately as possible on different testing occasions could approximate sampling from the same motor unit, although the reliability of this approach has not been established.

In addition, functional wavelet analysis offers the possibility of measuring neuromuscular recruitment patterns in greater detail than conventional sEMG analysis allows through resolving the EMG frequency spectrum. It enables evaluation of the relative activation of different neuromuscular components such as fast and slow frequency motor units (Von Tscharner, 2000) which exhibit different activity-dependant recruitment and fatigue patterns (Wakeling, Pascual, Nigg, & Von Tscharner, 2001). This differentiation would be a novel and valuable approach to evaluating the effects of fatigue, injury and interventions. Wavelet analysis is increasingly utilised in animal and human research, although its reliability in humans has not been previously established. Statistical characteristics of the sEMG wavelet analysis measure would also inform the required sample size.

Motor unit action potentials (MUAPs) sum to produce an electromyographic (EMG) signal (Calder, Agnew, Stashuk & McLean, 2008). Evaluating motor unit characteristics using in

dwelling or surface electrodes provides information about neuromuscular function, such as muscle activation timing, frequency, intensity (force) and motor unit recruitment patterns (Von Tschanner, 2000; Wakeling, Kaya, Temple, Johnson & Herzog, 2002). The EMG median frequency (the point at which the EMG signal could be equally divided into two) is significantly related to MUAP velocity, muscle temperature, muscle fatigue and fibre type (Pincivero, Green, Mark & Campy, 2000), making it a valuable point of reference. However, it is possible to observe a constant mean myoelectric frequency, alongside a graded change in MUAP conduction velocity (Wakeling & Rozitis, 2004), and 'averaging' the EMG frequency does not necessarily provide an accurate representation of fast and slow motor unit recruitment patterns over time.

Wavelet transformation of EMG simultaneously resolves myoelectric signals in time and frequency space, differentiating between slow and fast MUAPs and evaluating the frequency spectrum in more detail (Tole, 2007a; Wakeling et al., 2002). The EMG signal can be considered as two principal components: the fundamental spectral shape (PCI), which is a measure of the overall intensity, and frequency content (PCII) (Wakeling & Rozitis, 2004). Principal component analysis of the relative PCI and PCII scores describe the main frequency components of each spectrum (Wakeling & Rozitis, 2004) and the ratio of EMG intensity (PCI) to signal frequency content (PCII) can indicate the type of active motor unit (Tole, 2007a). Wakeling & Syme (2002) identified a low frequency band of 75-194 Hz and a high frequency band of 192-364 Hz, corresponding with slow and fast motor unit activation respectively, showing a significant difference between the means of these myoelectric intensity spectra. Time-frequency analysis of a filter bank of non-linearly scaled wavelets enables distinction between the low and high frequency spectra of muscle activation (Von Tschanner, 2000). In a bank of 11 wavelets the ratio of the cumulative powers of wavelets 2-4 (low frequency) and wavelets 8-10 (high frequency) can indicate the relative recruitment of slow and fast twitch muscle fibres (Tole, 2007a).

'Voluntary effort' is a potential source of bias inherent to many outcome measures assessing muscle function. There is no evidence to suggest that individuals can influence the pattern of fast and slow motor unit recruitment within muscles, which eliminates voluntary bias and poses functional sEMG analysis as a favourable approach to analysing muscle function.

Available literature suggests functional wavelet analysis of sEMG is increasingly utilised in human and animal studies, although its application has not extended to sport science and medicine practice. Functional sEMG analysis is a reliable measure in fish, where slow and fast fibres are anatomically separated (Wakeling et al., 2002), however the approach is much less utilised in humans where motor units are of mixed and varied fibre type composition.

Aims and objectives

The aim of this study was to determine the reliability of sEMG wavelet analysis in measuring the relative intensity of slow and fast motor unit recruitment in human lower limb muscles.

The objectives were:

1. To determine if there is a measurable difference in the relative intensity of slow and fast motor unit recruitment

2. To determine the reliability of the EMG wavelet analysis technique on different testing occasions
3. To determine the reliability of sEMG when electrodes are removed and replaced between tests

3.2.2 Method

Participants and study design

In a repeated measures design, 12 participants completed three familiarisation trials followed by two testing trials on consecutive days, within a seven day period. Ethics approval was obtained from the University of Bath School Research Ethics Committee and volunteer participants provided informed written consent.

Experimental protocol & data management

Electrode placement

Electrodes were positioned mid-belly on medial gastrocnemius (MG), vastus lateralis (VL), vastus medialis (VM) and biceps femoris (BF), in a parallel direction to muscle fibre orientation according to the protocol described by Rainoldi, Melchiorri & Caruso (2004). During Trial 1, electrode position was traced with a permanent marker and electrodes were replaced in exactly the same position for Trial 2 the next day.

Muscle dynamometry

Participants were seated upright on the Biodex® dynamometer with torso, pelvic and leg straps secured to reduce extraneous body movements. Chair settings, dynamometry attachment and joint angles were recorded for each subject and maintained the same on each trial occasion. Participants performed 3 X 5 second isometric muscle actions at 80% of their maximal voluntary contraction (MVC) at the following joint angles on the Biodex®, with 30sec recovery between contractions:

1. 15° ankle plantarflexion (PF)
2. 20° knee extension (KEXT)
3. 20° knee flexion (KFL)

These positions were selected as they replicate functional joint angles. Additionally, peak isometric torque of the knee flexors is optimal between 15 and 30 degrees (Onishi, Yagi, Oyama, Akasaka, Ihashi & Handa, 2002). An MVC force was established for each subject in each position during familiarisation, from which 80% MVC force value was calculated. A visible line was placed on the Biodex® screen at 80% MVC. Participants were instructed to produce and sustain a force as close as possible to this line.

With constant muscle length and activation (represented by joint position and contraction force), variation in the sEMG signal should be attributable to physiological changes in neuromuscular activation or measurement error.

sEMG

sEMG data was collected and recorded during 80% MVCs, using the Telemetry® EMG at a rate of 3000Hz per second. This sampling frequency ensured collection of the whole signal from the muscle (Tole, 2007b). The raw sEMG signal was band-passed filtered at 20-500Hz.

sEMG data was analysed from each muscle in its primary contracting position: PF – MG; KEXT – VM & VL; KFL – BF. To examine the sEMG in the time domain, the 1 second raw sEMG signals for each muscle were processed through root mean square (RMS) and integrated EMG (iEMG) calculations over a 50ms time constant. Intensities of myoelectric signals were resolved into time/frequency space with wavelet analysis (Von Tscharner, 2000) using the Wavelet3000 programme (Tole, 2007c) in Matlab™ statistical software. Of an 11 wavelet filter bank, the intensities of wavelets 2-4 and 8-10 were summed to represent the low and high frequency spectra respectively. The ratio of low:high frequency wavelet intensities was calculated to determine the relative intensities of slow and fast motor unit recruitment (iWR).

Data analysis

One second intervals of consistent force production were identified from the Biodex® time-force log: one interval from a contraction during Trial 1 (Trial 1) and two intervals from different contractions during Trial 2 (Trial 2 and Trial 2B). Simultaneous RMS, iEMG and iWR metrics of the sEMG signal for this window were isolated for analysis.

Using the method described by Hopkins (2000b), a one way analysis of variance (ANOVA) compared the RMS, iEMG and iWR between Trials 1-2 (between day) and Trials 2-2B (within day). A two tailed paired t-test compared the difference in means between Trials 1-2 and Trial 2-2B. The significance level was set at 0.05. The intra-class correlation co-efficient (ICC) was used to represent the relative test-retest reliability. Absolute reliability was expressed as a percentage coefficient of variation (%CV) and categorised according to McInnes, Carlson, Jones & McKenna (1995) classification of good <5%, moderate 5-9.9%, or poor >10%. Statistics describing 'absolute reliability', such as the coefficient of variation (CV), are unaffected by the range of measurements and can be extrapolated to different measurement tools and populations (Atkinson & Nevill, 1998), which can be of greater relevance to sport science practice than variation in raw scores (Hopkins, 2000a).

3.2.3 Results

Reproducibility of 80% iMVC

The percentage error in reproducing the pre-calculated 80% MVC in different trials is contained in Table 3.1. There was a low mean error of 1.1%-2.5% in force reproduction during Trials 1, Trial 2 and Trial 2B.

Table 3.1 Percentage error of reproducing the pre-calculated 80% MVC in different trials

The mean, minimum and maximum percentage error in reproducing the pre-determined 80% MVC are shown; for plantarflexion (PF), knee extension (KEXT) and knee flexion (KFL); in one interval from a contraction in each of trial 1 (Trial 1) and two intervals from different contractions during trial 2 (Trial 2 and Trial 2B).

	PF			KEXT			KFL		
	Trial 1	Trial 2	Trial 2B	Trial 1	Trial 2	Trial 2B	Trial 1	Trial 2	Trial 2B
Mean	1.1%	1.3%	1.5%	1.6%	1.7%	1.9%	1.4%	2.1%	2.5%
Minimum	0.5%	0.6%	0.5%	0.7%	0.7%	0.4%	0.6%	0.2%	0.9%
Maximum	1.8%	5.3%	3.8%	3.8%	3.4%	4.8%	3.1%	5.3%	6.3%

EMG metrics

The trial mean and 95% Confidence Interval (CI) are illustrated for metrics of the electromyographic (EMG) signal root-mean-square (RMS), Figure 3.1; integrated (iEMG), Figure 3.2; and low:high intensity wavelet ratio (iWR), Figure 3.3.

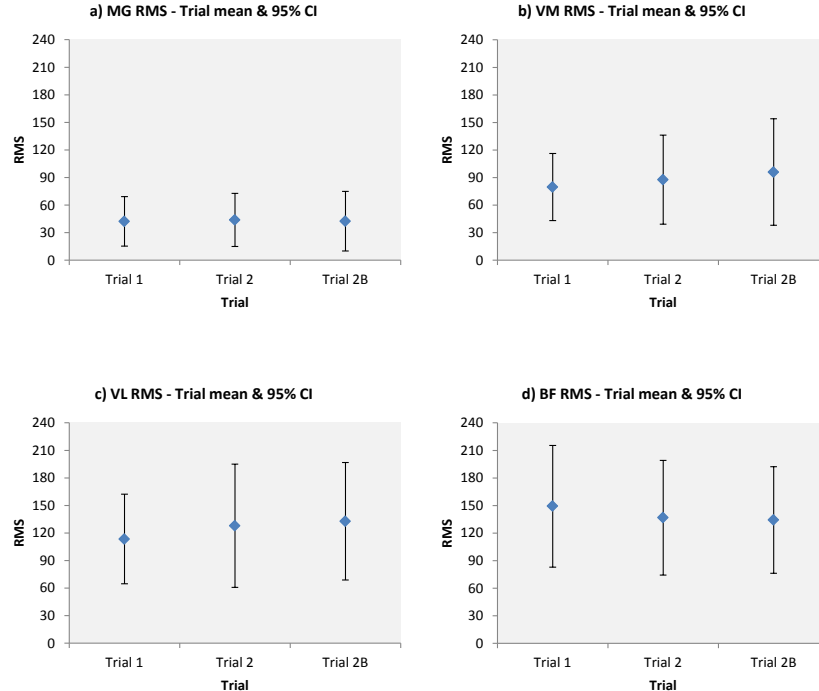


Figure 3.1 RMS value of the EMG signal - trial mean and 95% CI for muscles a) MG, b) VL, c) VM, d) BF

For Trial 1, Trial 2 and Trial 2B, the mean and 95% Confidence Interval (CI) of the root-mean-square (RMS) value of the electromyographic (EMG) signal are illustrated for muscles a) medial gastrocnemius (MG), b) vastus lateralis (VL), c) vastus medialis (VM) and d) biceps femoris (BF).

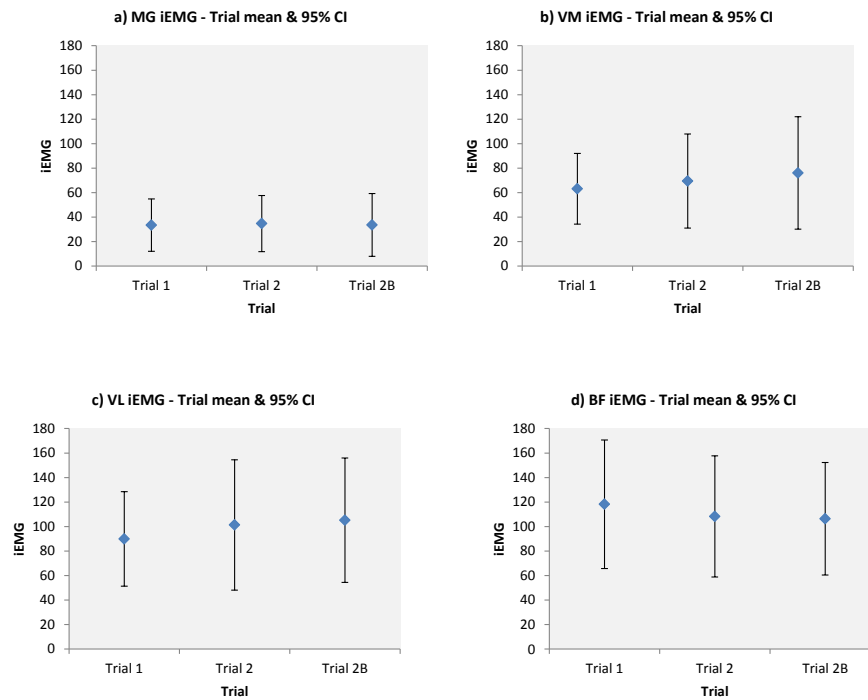


Figure 3.2 iEMG value of the EMG signal - trial mean and 95% CI for muscles a) MG, b) VL, c) VM, d) BF
For Trial 1, Trial 2 and Trial 2B, the mean and 95% Confidence Interval (CI) of the integrated electromyographic signal (iEMG) are illustrated for muscles a) medial gastrocnemius (MG), b) vastis lateralis (VL), c) vastis medialis (VM) and d) biceps femoris (BF).

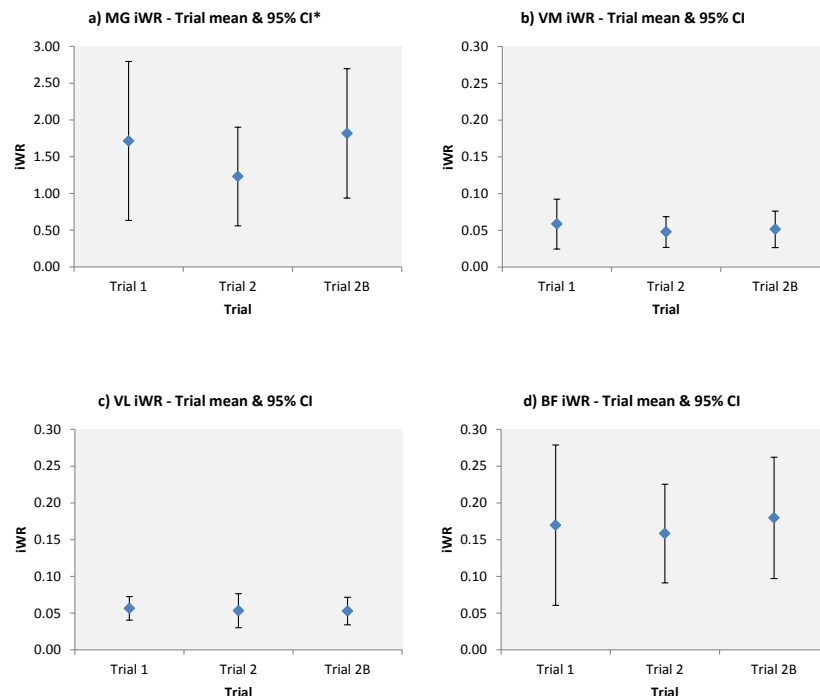


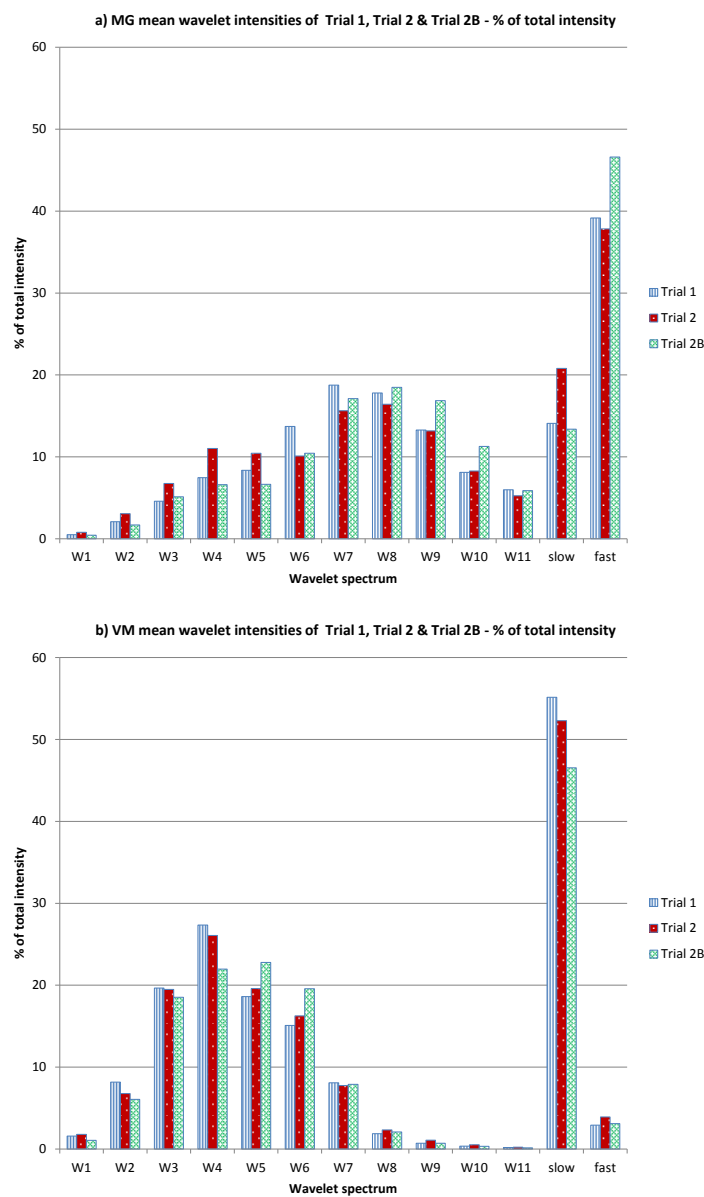
Figure 3.3 iWR value of the EMG signal - trial mean and 95% CI for muscles a) MG, b) VL, c) VM, d) BF
For Trial 1, Trial 2 and Trial 2B, the mean and 95% Confidence Interval (CI) of the low:high frequency wavelet intensity ratio (iWR) value of the electromyographic (EMG) signal are illustrated for muscles a) medial gastrocnemius (MG), b) vastis lateralis (VL), c) vastis medialis (VM) and d) biceps femoris (BF).

*note adjustment of vertical axis scale for visual purposes

Figure 3.4 illustrates the 11 wavelet resolution of the EMG signal for muscles a) MG, b) VL, c) VM and d) BF. Individual wavelet intensities are shown as a percentage of the total EMG intensity, alongside the sum of wavelets 2-4 (low frequency) and wavelets 8-10 (high frequency) representing slow and fast motor units respectively. Trial 1, Trial 2 and Trial 2B are shown on the same axis to facilitate visual between-trial comparison.

Figure 3.4 Mean intensities of the 11-wavelet bank and slow/fast motor unit representation for muscles a) MG, b) VL, c) VM, d) BF

The 11 wavelet resolution of the surface electromyographic (sEMG) signal are distinguished in human muscles a) medial gastrocnemius (MG), b) vastis lateralis (VL), c) vastis medialis (VM) and d) biceps femoris (BF), and further distinguished as relative intensity of low (sum of wavelets 2-4) and high (sum of wavelets 8-10) frequency spectra. For Trial 1, Trial 2 and Trial 2B, individual wavelet intensities are shown as a percentage of the total EMG intensity, alongside the sum of wavelets 2-4 (low frequency) and wavelets 8-10 (high frequency) representing slow and fast motor units respectively.



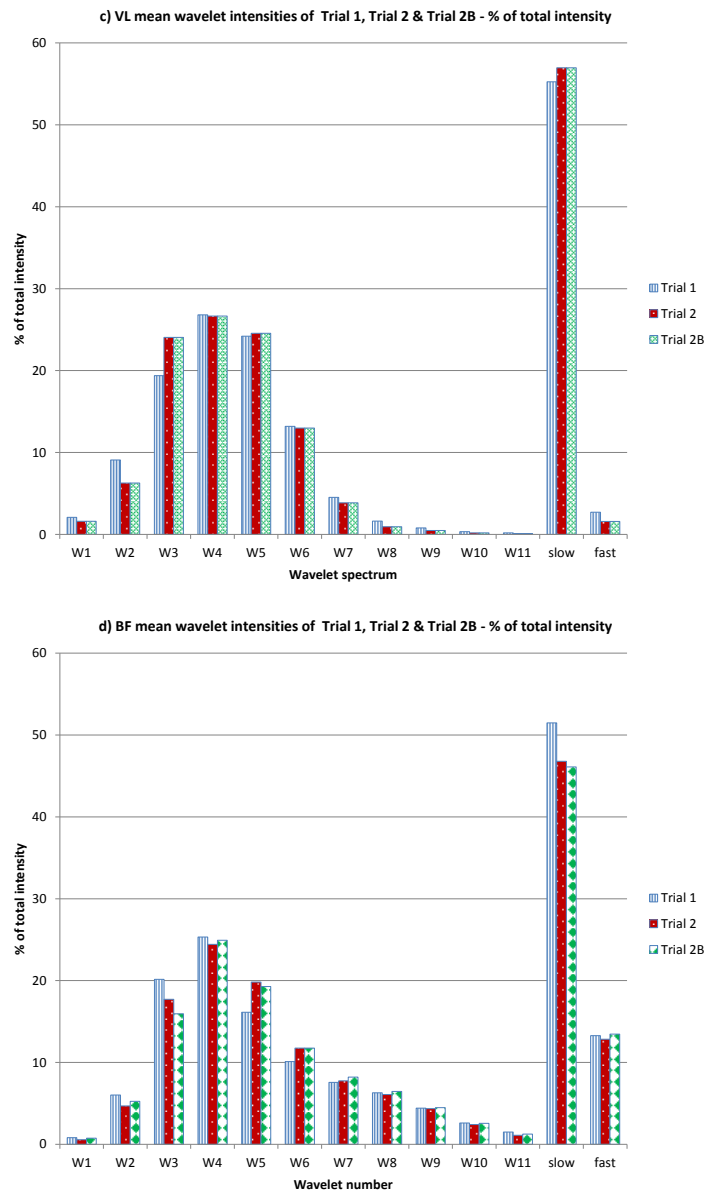


Figure 3.4 shows that the relative intensity of the 11 wavelet bank could be distinguished in humans, and further distinguished as relative intensity of low frequency (sum of wavelets 2-4) and high frequency (sum of wavelets 8-10) motor unit recruitment. Mean iWR for VM (0.05-0.06), VL (0.05-0.06) and BF (0.16-0.18) indicated greater relative intensity of low frequency motor units in the sEMG signal. MG displayed a typically larger iWR (mean 1.2-1.8), indicating a greater relative intensity of high frequency (fast) motor units in the sEMG signal. A greater variation in the relative intensity of low and high frequency spectra was observed in MG and BF than the vastii.

Data were not normality distributed. Heteroscedasticity was apparent from graphical representation of the RMS and iWR. Therefore the log transform of the data was used for analysis and the typical error of measurement expressed as a percentage deviation from the mean. Table 3.2 summarises the difference in means between days (Trial 1-2) and within days (Trial 2-2B).

Table 3.2 Between-trial reliability of root-mean-square (RMS), integrated (iEMG) and slow:fast wavelet intensity ratio (iWR) metrics of the EMG signal for muscles MG, VL, VM & BF: typical error, confidence interval, ICC and paired t-test.

For muscles medial gastrocnemius (MG), vastus medialis (VM), vastus lateralis (VL) and biceps femoris (BF), comparison of root-mean-square (RMS), integrated (iEMG) and low:high frequency wavelet intensity ratio (iWR) metrics of the EMG signal between Trial 1 and Trial 2 represent between-day reliability. Comparison between Trial 2 and Trial 2B represent within-day reliability. The coefficient of variation (CV) describes the ‘absolute reliability’ and the typical error of measurement is expressed as a percentage deviation from the mean. The intra-class correlation co-efficient (ICC) represents the relative test-retest reliability. A two tailed paired t-test compared the difference in means between Trials 1-2 (between day) and Trial 2-2B (same day), and the *p* values are shown.

EMG Metric	muscle	n	Trial 1-2			Trial 2-2B			Paired t-test
			Typical error as CV	CV confidence interval	ICC	Typical error as CV	CV confidence interval	ICC	<i>p</i> value
RMS	MG	11*	36	26 - 63	0.90	36	26 - 62	0.92	0.98
	VM	12	36	26 - 62	0.85	10	8 - 17	0.98	0.97
	VL	12	31	22 - 53	0.84	11	8 - 19	0.97	0.83
	BF	12	24	18 - 40	0.88	14	10 - 23	0.96	0.71
iEMG	MG	11*	36	26 - 63	0.90	36	26 - 62	0.92	0.98
	VM	12	36	26 - 62	0.85	10	8 - 17	0.98	0.97
	VL	12	31	22 - 53	0.84	11	8 - 19	0.97	0.83
	BF	12	24	18 - 40	0.88	14	10 - 23	0.96	0.71
iWR	MG	11*	30	22 - 53	0.89	64	45 - 115	0.62	0.03
	VM	12	66	46 - 119	0.62	23	17 - 37	0.92	0.32
	VL	12	48	34 - 86	0.61	27	19 - 46	0.86	0.83
	BF	12	40	29 - 68	0.86	44	31 - 75	0.82	0.50

*EMG data recorded from the MG muscle (only) of one participant was of immeasurably low signal and could not be considered for analysis. Therefore n=11 for analysis relating to the MG muscle.

Comparison of between-day Trials 1 and Trial 2 when electrodes were removed and replaced, RMS and iEMG had ICC values of 0.84-0.90 for all muscles. iWR had lower ICC values of 0.61-0.89. The typical error range for RMS & iEMG was 24-36% and iWR 30-66%.

Comparison of within-day Trial 2 and Trial 2B (consecutive contractions) when electrodes remained in situ, RMS and iEMG had high ICC values of 0.92-0.98. This was higher than between Trials 1-2 (0.84-0.90). For VM, VL, & BF RMS and iEMG measurement errors of 10-14% were also lower than observed between Trials 1-2 (24-36%). For MG the measurement error was 36% between Trials 1-2 and Trials 2-2B. Reliability of within-day iWR closely approximated that seen between Trials 1-2, with ICC range of 0.62-0.92 and a typical error of 23-64%.

Defined by ICC>0.8 (Atkinson & Nevill, 1998), high reliability was observed in RMS and iEMG between Trials 1-2 and 2-2B. High reliability was also observed for iWR between Trials 1-2 for MG (0.89) & BF (0.86), and between Trials 2-2B VM (0.92), VL (0.86) & BF (0.82). Reliability expressed as a %CV was poor (>10%) for all trials and all muscles according to McInnes et al., (1995) classification. With the exception of MG, there was no significant difference between Trial 1-2 and Trial 2-2B differences in mean RMS, iEMG and iWR (*p*>0.05).

The RMS and iEMG metrics had a higher ICC and lower %CV than iWR. This observation was evident in trials on the same day, and more pronounced between days.

3.2.4 Discussion

The results of this study unequivocally indicate that sEMG wavelet analysis can distinguish between fast and slow motor unit recruitment in humans. However, either large measurement error was associated with iWR; or the same activity in controlled conditions, producing the same force, can be achieved using different patterns of neuromuscular recruitment.

The correlation between measurements taken on different days was used to evaluate the reliability of sampling and analysis of motor units from the same anatomical site, which approximated sampling from the same motor units. RMS and iEMG showed good to high statistical correlation both within and between day Trials ($ICC > 0.84$). However, it is difficult to accept these as reliable measures with typical measurement errors of 24-36%, presenting sEMG as an unreliable approach to assessing individuals and evaluating change in muscle recruitment. There was typically greater difference between trials where the electrodes were removed and replaced, than when they remained in situ.

This investigation had the particular objective of evaluating the reliability of the sEMG wavelet analysis technique. The iWR had a low correlation both within and between days, and an unacceptable measurement error of 23%-66%.

The findings did not reflect the assumption that sampling from the same motor unit enables repeatable functional sEMG analysis. The ratio of fast:slow motor units recruitment differed between trials even when electrodes remained in situ and testing conditions were unchanged. This represents either an unacceptable degree of measurement error or biological variation in the ratio of fast:slow motor units recruited to produce the same performance outcome (isometric force in this instance).

It is particularly difficult to attribute the large within-day variation solely to measurement error in these controlled conditions with consecutive, sub-maximal contractions. The observations more strongly infer that under the same conditions, the same force can be achieved via different recruitment patterns. This variability makes measurement and evaluation of motor unit recruitment all the more valuable in informing practice. It would be interesting but difficult to quantify the degree of variation inherent to complex movement patterns and sport performance.

The iWR was not necessarily associated with a greater percentage measurement error than the accepted EMG metrics of RMS and iEMG, and on this basis its application to practice could be justified. Further exploration and refinement of measurement protocols could improve the reliability of sEMG wavelet analysis to at least the level of conventional EMG analysis. This is a worthwhile pursuit as sEMG wavelet analysis offers a novel opportunity to differentiate motor unit recruitment patterns in the practice setting.

The iWR was not considered adequately stable for application in the experimental evaluation of intervention effects or assessment of neuromuscular recruitment patterns in individuals. However comparison between population groups (for example explosive volleyball players and endurance runners) or observation of longitudinal trends could significantly contribute to the

neuromuscular recruitment and performance knowledge base. Wavelet intensity general patterns were evident in the fast or slow motor unit recruitment. VM and VL were low frequency dominant, BF was more variable but low frequency dominant, while MG showed more mixed recruitment. Expected ratios of low:high frequency motor unit recruitment for various muscles and activities have not been previously quantified, and wavelet analysis could be useful in identifying typical neuromuscular recruitment patterns. Although inferences can be made from the findings of this study, more normative data is needed to describe these characteristics.

3.2.5 Conclusion

sEMG wavelet analysis can distinguish between fast and slow motor unit recruitment in humans. Repeatability was lower when electrodes were removed and replaced, than when they remained in situ. Variation >10% indicated either that measurement error was large; or the same force can be produced using different patterns of neuromuscular recruitment. Between test reliability was not acceptable for the precision required in sports medicine and science practice or experimental evaluation of intervention effects.

3.3 Chapter summary

The outcomes of this study suggest that wavelet analysis can resolve the high and low frequency spectrum within sEMG signal to represent the recruitment of fast and slow motor units in humans. The RMS and iEMG metrics appeared more repeatable than iWR, although it may be difficult to distinguish physiological variation from measurement error. Although statistically non-significant, this observation was evident in tests on the same day and more pronounced between days when electrodes were removed and replaced. The iWR has questionable statistical correlation and a high percentage error between tests, and as such does not present a reliable measurement tool.

Chapter 4 STUDY 2: THE EFFECT OF WATER IMMERSION ON RECOVERY FROM INTERMITTANT SHUTTLE RUNNING - STUDY DESIGN AND METHODS

4.1 Experimental design

Following a bout of intense exercise for 90 minutes, two water immersion recovery interventions and rest (control) were compared in a repeated measure randomised cross over design. Outcome measures were recorded prior to intense exercise (Pre-Exercise), immediately following intense exercise (Post-Exercise) and at 2 hours, 4 hours and 24 hours post exercise.

Participants attended the University of Bath on five occasions within a six week period. Two occasions were for familiarisation to the testing procedures followed by three main trials. Although it was not possible to blind to the intervention itself, participants were informed upon recruitment that clinical equipoise is genuinely unclear. They were blinded to the researchers' hypotheses and results until completion of the study.

Replicating current practice and the demands on high performance athletes was central to this project. This required a detailed description of participant characteristics, test-exercise bout and trial conditions which contribute to the external validity of the results and application to practice.

4.2 Sample size

There was no previous data to accurately estimate the effect size of water immersion recovery interventions on neuromuscular function of the lower limb, using force plate or muscle dynamometry parameters. Sample size calculation was therefore based on muscle dynamometry data recently collected in our laboratory and an assumption of what constitutes a meaningful functional difference in peak torque production.

For the proposed 20⁰ knee flexion tests in this study, a pilot study determined the mean within-subject variation in trials on consecutive days as 0.8Nm or 1%, and the standard deviation as 14.5N.m or 38% (Appendix 1). This mean variation was consistent with evidence attributing MVC variation below 5% to natural variation and above 5% to neuromuscular fatigue (Morton et al., 2005), however the standard deviation suggests a greater natural variation of 14.5Nm or 38% could be reasonably expected. Therefore a conservative proposal of the smallest meaningful difference attributable to an intervention was above 14.5Nm.

Based on a SD estimate of 14.5Nm, and a smallest worthwhile change of 20Nm, (effect size 1.4) a sample size of 11 would be sufficient to show a significant difference (with 80% power and $\alpha = .05$) in this study¹.

4.3 Ethics

Ethics approval was obtained from the Bath NHS Local Research Ethics Committee (LREC) and the University of Bath School for Health Research Ethics Committee (SREAP).

4.4 Participants

Written informed consent was obtained from 11 male volunteers (age 20 ± 2.5 years, height 187 ± 12 cm, weight 81 ± 8 kg, Beep Test Level 11.5 ± 1.3 , estimated maximal oxygen uptake (VO_2max) 52 ± 4 $\text{mL.kg}^{-1}.\text{min}^{-1}$). All were non-smoking, active males who habitually competed at high level in their chosen sports. Eight participants were on nationally funded talent identification programmes (3 beach volleyball; 1 judo; 1 badminton; 1 tennis; 2 middle distance athletics) and three competed at British University Sports Association level (3 University first team rugby). Table 4.1 contains participants' age, height, weight and aerobic fitness characteristics.

Table 4.1 Relevant participant characteristics

The mean \pm standard deviation (SD) and Range are shown for relevant characteristics of the 11 male study participants. All were non-smoking, active and habitually competed at high level in their chosen sports.

[†]L denotes Beep Test completed level; S denotes shuttles of partially completed level.

	Mean \pm SD	Range
Age (years)	20.3 ± 2.5	18-26
Height (cm)	187 ± 12	177-208
Weight (kg)	81.3 ± 8.3	67-97
Beep Test Score	11.5 ± 1.3	L9.S11-L14.S2 [†]
VO_2max ($\text{mL.kg}^{-1}.\text{min}^{-1}$)	52.2 ± 4.2	46.8-61.2

Participants were considered representative of the target athletic population. Although this could have decreased the size of the effect, for external validity and application to the athletic community it was necessary to replicate this familiarity and test the efficacy in accustomed individuals as physiological responses to exercise are training dependent (Blannin et al., 1996; St. Pierre Schneider & Tiidus, 2007). Some recent studies have evaluated water immersion recovery interventions using untrained subjects (Sellwood et al., 2007) or unaccustomed exercise (Bailey et al., 2007) which may anticipate a larger effect size (McHugh, 2003; Newham et al., 1987; Sacco & Jones, 1992) and facilitate identification of statistically significant findings.

¹ Furthermore, various studies in our laboratory have used the LIST exercise protocol, showing an exercise effect size of 1.3-1.7 on knee flexion MVC at 20° (difference in means pre-post exercise SD 18-26Nm) (Betts et al., 2009). This data suggests a sample of 11-17 would also be appropriate to show significant change pre and post exercise.

However, this does not necessarily replicate the effects on athletes who are accustomed to intense exercise and familiar with a range of recovery interventions.

Due to the intense exercise and water immersion intervention in this study, all individuals completed the Par-Q health questionnaire and were free of any medical conditions affected by exposure to cold (eg Raynaud's disease). No volunteers were excluded on the basis of health.

Females were excluded from the study to avoid any confounding influence associated with the menstrual cycle. Although no significant gender difference has been shown between contractile force and muscle function (Wakeling & Rozitis, 2004), oestrogen can affect skeletal muscle damage, inflammation and repair (Kendall & Eston, 2002; Tiidus, 2005).

4.5 Preliminary measures and familiarisation

On the first preliminary test participants completed the Beep Test, which is an incremental shuttle running exercise test to volitional fatigue. Attainment of a minimum score of Level 9.11 was set to participate in the main trial, equivalent to a predicted maximum oxygen uptake (VO_2max) of 46.8ml per kg body mass per minute (Ramsbottom, Brewer & Williams, 1988). For the 20-29 year old age group, participants could therefore be categorised as "excellent" (VO_2max 46.5-52.4 $\text{mL.kg}^{-1}.\text{min}^{-1}$) or "superior" (VO_2max > 52.4 $\text{mL.kg}^{-1}.\text{min}^{-1}$) (The Cooper Institute for Aerobic Research, 1997). Furthermore, while the multistage fitness test is reliable, it tends to underestimate VO_2max (Cooper, Baker, Tong, Roberts & Hanford, 2005). This minimum fitness criterion was to ensure recruitment of a trained athlete population, gauge volunteers' capability of completing the 90 minute shuttle running protocol required in the main study, and to estimate VO_2max . Predicted VO_2max was calculated from participants' Beep Test scores, according to the method described by Top End Sports (2009).

On the second preliminary test subjects were familiarised to the Loughborough Intermittent Shuttle Test (LIST; described fully within the experimental protocol), completing the 90 minute shuttle run protocol under trial conditions. Following the LIST, all participants completed five minutes of continuous immersion to the shoulders in each of warm water and cold water.

A known phenomenon is the typically larger physiological response following unaccustomed activity, and the 'repeated bout effect' describes the protective or dampened response that may be observed in subsequent similar exercise bouts (McHugh, 2003; Newham et al., 1987; Sacco & Jones, 1992). To stimulate protective adaptation the initial bout need not cause damage but must be close to maximum contraction intensity; and be specific to the exercised muscle groups but not necessarily the same exercise manner (McHugh, 2003). Although much evidence describes the repeated bout effect relating to unaccustomed or eccentric exercise, trained athletes report muscle soreness following the LIST on the first occasion (Thompson et al., 1999).

To avoid a trial order effect recent studies have separated trials by 8 months (Vaile et al., 2008) or used matched pairs designs (Bailey et al., 2007; Ingram et al., 2009). However, equivalency of the physical status of subjects during generously spaced trial occasions is questionable as

significant natural variation with time or across a sporting season could reasonably be expected. While matched pair designs provide an alternative, the strengths of evaluating the same athletes in a cross over design is sacrificed.

Therefore although all participants were familiar with the demands of team sports, intermittent exercise patterns and were habitual users of water immersion recovery interventions, familiarisation to specific exercise-test and water immersion protocol of this study (described fully in the experimental protocol) aimed to avoid an excessive response in the first trial.

At least 2 familiarisation trials to the muscle dynamometry and force plate jump protocols (described fully within experimental protocol) were completed and maximum voluntary contraction (MVC) knee extension (KE) and knee flexion (KF) forces were established for each participant. Based on stability of this data and that of previous familiarisation trials (Betts, Toone, Stokes & Thompson, 2009), this familiarisation protocol was sufficient in eliminating the influence of improvements due to practice and learning.

4.6 Experimental protocol

Figure 1.1 provides a schematic representation of the study design. Participants arrived at the laboratory between 8am and 9am on testing days. Tests were administered at the same time of day to minimise diurnal variance (American College of Sports Medicine (ACSM), 2006; Winter, Jones, Davison, Bromley & Mercer, 2007). Pre-Exercise outcome measures were recorded, followed by completion of the Loughborough Intermittent Shuttle Test (LIST) exercise protocol and Post-Exercise outcome measures. In a randomised cross-over design, participants then undertook interventions of cold water immersion, warm water immersion or passive recovery (rest). Recovery over 24 hours was evaluated from analysis of circulating markers of muscle damage (Chapter 5), neuromuscular function (Chapter 6) and perceived recovery (Chapter 7).

4.6.1 Outcome measurement

Outcome measure time-points were Pre-Exercise (Pre-Ex), Post-Exercise (Post-Ex), 2 hours, 4 hours and 24 hours post exercise. The typical post-exercise time-course of circulating markers of muscle damage is well established and these time-points correlate with times where observation of difference may be expected (Gleeson, 2007; Mougios, 2007; Neubauer, Konig & Wagner, 2008). Furthermore, 2 hours, 4 hours and the next morning represent intervals of interest in practice, where athletes may reasonably be expected to participate in subsequent training or competition bouts.

Venepuncture

Participants lay supine on a plinth for 15 minutes prior to venous blood sampling. This maintained consistent posture and immediate pre-sample behaviour between tests, avoiding confounding the results with orthostatic influences such as peripheral blood volume and compartmental fluid shifts. Consequently, the Post-Exercise measure was consistently 15 minutes post-exercise. Venous blood is more reflective of whole body responses than capillary blood, and was therefore the sample of choice.

Venepuncture was performed according to standard operating procedures. A tourniquet was applied to the upper arm, a viable ante-cubital vein identified and the skin cleaned with an alcohol wipe (Steret™). The tourniquet was released, and reapplied immediately prior to venepuncture. A 10mL blood sample was drawn using a butterfly needle and syringe. 5mL of blood was immediately dispensed into each of EDTA and serum vacutainers, placed on ice and transported to the laboratory.

Venepuncture was not performed at the 2 hour post-exercise time-point. Over a 24 hour period across 3 test trials separated by 7-14 days, it was reasonable to limit administration of this relatively invasive procedure to the most relevant time-points to evaluate change. These were Pre-Ex, Post-Ex, 4 hours and 24 hours. These time-points coincided with anticipated post-exercise peaks of circulating markers of muscle damage, facilitating evaluation of the recovery time-course. Myoglobin was expected to peak immediately post-exercise and remain elevated at 4 hours post exercise (Neubauer et al., 2008; Betts et al., 2009) and the CK peak was anticipated at 24 hours (Mougios, 2007).

In the laboratory, the EDTA plasma sample was analysed for glucose and lactate (YSI 2300 Stat Plus; YSI Incorporated, Yellow Springs, Ohio), leukocytes and erythrocytes (Sysmex SF-3000; Kobe, Japan). Whole blood - EDTA plasma and serum vials - was centrifuged for 10 minutes, 5000r/s, at 4°C (Biofuge Primo R, Heraeus). Serum and plasma were separated from the blood protein using a pipette, and stored in small aliquots. Aliquots were frozen at -18°C. Serum aliquots were later defrosted in batches, and analysed for CK activity and myoglobin concentration using commercially available enzymatic colorimetric assays (Randox) with an automated spectrophotometric analyser (Cobas Mira; Roche, Switzerland).

CK and myoglobin assay preparation

CK was determined using creatine phosphate and adenosine-5'-diphosphate (ADP) as substrates (Randox, 2007a). Enzymes/Coenzymes/Substrate R1b was reconstituted with the appropriate volume of Buffer/Glucose according to manufacturer instructions (Randox, 2007a). Three levels of cardiac controls were reconstituted according to manufacturer instructions (Randox, 2008).

Latex Enhanced Immunoturbidimetric Assay for Serum Myoglobin (Randox) was prepared according to manufacturer instructions (Myoglobin Assay Buffer, Myoglobin Latex Reagent, Randox Myoglobin Callibrator Series, Randox Tri Level Cardiac Controls). Normal levels in serum are usually less than 85ng/ml and the assay range was 20-725ng/ml (Randox, 2007b). Samples returning a reading higher than this level were diluted 1+3 and factored x 4.

Warm up

Following venepuncture and prior to muscle function testing, subjects completed a standardised warm up of 5 minutes stationary cycling followed by stretching the hamstrings and quadriceps muscle groups for 1 minute each.

Muscle dynamometry

Muscle dynamometry tested maximal isometric knee extension and knee flexion torque. Participants were seated upright on the Humac Norm® muscle dynamometer with torso, pelvic and leg straps secured to reduce extraneous body movements. Chair settings, dynamometry attachment and joint angles were recorded for each subject and maintained the same on each trial occasion. The Humac Norm® was calibrated according to manufacturers' instructions before each test to account for limb weight and the influence of gravity on torque.

Participants performed 5 x 5 second isometric maximum voluntary contractions (iMVCs) for each of the following actions, with 10 seconds recovery between contractions.

1. Knee extension (KE) at 60°
2. Knee flexion (KF) at 20°

Anatomical 0° was defined as 0° knee extension. These positions are illustrated in Figure 4.1.

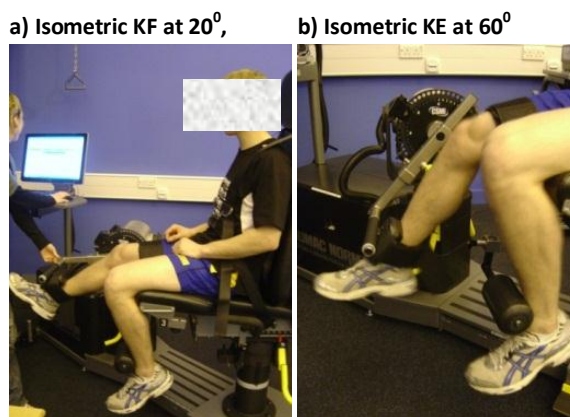


Figure 4.1 Muscle dynamometry test positions: a) Isometric KF at 20° , b) Isometric KE at 60°

Muscle dynamometry tested maximal isometric voluntary contraction (iMVC) torque of knee flexion (KF) at 20° and knee extension (KE) at 60° .

These positions were selected as they represent functional joint angles and knee flexion peak isometric torque is between 15 and 30 degrees (Onishi et al., 2002). Previous work tested similar and various protocols before settling on these angles, and muscle function has been shown to decline by 10-20% following the LIST using this protocol (Betts, Toone, Stokes & Thompson, 2009).

Participants were given verbal encouragement, by the same investigator, to produce maximum voluntary force. Visual feedback on the Humac Norm® screen was obscured from view to avoid influence of MVC performance feedback on maximal effort.

Data management

Data derived from complete repetitions only were isolated for analysis. Data were smoothed with a moving average of 100ms. *Peak torque* (Nm) was identified and defined as the maximum torque value from the time-force history. All data were reported as torques as inaccuracies can be associated with calculating the length of the moment arm and converting the data to force Unit measures.

Performance tests

Each participant performed 3 drop jumps (DJ) from a 30cm box (Figure 4.2) and a series of 6 maximal single leg hops (RH) from a force plate (Figure 4.3). Drop Jump and single leg hop series are considered reliable measures of neuromuscular function (Augustsson, Thomeé, Lindén, Folkesson, Tranberg & Karlsson, 2006; Clark, Gumbrell, Rana, Traole & Morrissey, 2002; Maulder & Cronin, 2005; Orishimo & Kremenec, 2006). Detailed data management and definition of variables from force plate data is described fully in Chapter 6.

Drop Jump (DJ)

Participants stood with two feet on a 30cm high box positioned at the front of the force plate. The DJ protocol instructions were to step off the box, leading with the same leg on each occasion and jump as high as possible as quickly as possible from the force plate. Each participant performed 3 consecutive drop jumps at each outcome measure time-point. This is illustrated in Figure 4.2.

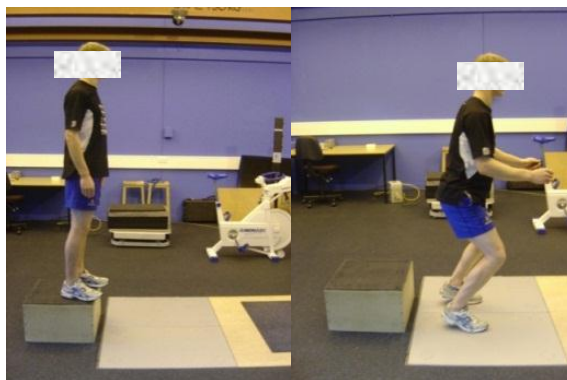


Figure 4.2 Force plate drop jump (DJ): starting position on a 30cm high box prior to step off; and contact phase

The drop jump (DJ) protocol instructed participants to step off a 30cm high box positioned at the front of the force plate, and jump as high as possible as quickly as possible from the force plate. The starting position and force plate contact phase between landing and take-off are shown.

Repeated Single Leg Hop (RH)

The RH protocol required participants to perform 6 successive hops on a force plate on their preferred leg. The instructions were to hop as high as possible, as quickly as possible and maintain the same position on the force plate. This is illustrated in Figure 4.3.



Figure 4.3: Force plate repeated single leg hop starting position

The starting position of the repeated single leg hop protocol (RH) is shown. Participants performed 6 successive hops on their preferred leg, hopping as high as possible, as quickly as possible and maintaining the same position on the force plate.

Perceived Fatigue and Perceived Recovery

On a visual analogue scale of 0-10, participants rated their Perceived Fatigue (PF) and Perceived Recovery (PR). The instructions were that:

“The PF rating should reflect how fatigued you feel. Combine all sensations and feelings of physical stress, soreness and tiredness. Try to focus on your total feeling of fatigue rather than individual factors. Look at the rating scale and choose the number that best describes your level of fatigue, where 0 means "no exertion at all" and 10 means "maximal fatigue".

and:

“The PR rating should reflect how recovered you feel. Try to focus on your total feeling of recovery rather than individual factors. Look at the rating scale and choose the number that best describes your level of recovery, where 0 means "not recovered at all" and 10 means “full recovery”. Full recovery was defined as “ready for participation in athletic activities at high intensity with maximal performance”.

Post-exercise muscle soreness is produced by several morphological and biochemical factors and a ‘tired, numb’ sensation versus ‘actual’ soreness can also be differentiated (Rodenburg et al., 1993). These descriptors of post exercise experiences are helpful but varied, and furthermore reduced muscle soreness and delayed onset muscle soreness (DOMS) could be expected following accustomed exercise (Sacco & Jones, 1992). Therefore in this study evaluating a trained, familiarised population, participants rated overarching perceived fatigue and perceived recovery on a visual analogue scale. Visual analogue scales (VAS) are recommended by the American College of Sports Medicine (ACSM) to measure exercise intensity (ACSM, 2008) and have been used as measures of perceived pain, fatigue and muscle soreness in previous studies evaluating recovery (Rowell et al., 2009; Vaile et al., 2008).

Preferred intervention

At the end of the study, in terms of feeling most recovered for athletic performance, participants were asked if they had a preferred and least preferred intervention of the three test interventions, and if so to nominate the preferred recovery condition.

4.6.2 Loughborough Intermittent Shuttle Test (LIST)

The type of exercise, including intensity and duration, is important when evaluating the post-exercise response (Nieman et al., 1994; Pedersen et al., 1998; St. Pierre Schneider & Tiidus, 2007) and therefore recovery pattern. Several recent comparable studies have evaluated water immersion intervention following eccentric-dominant exercise (Eston & Peters, 1998; Sellwood et al., 2007; Vaile et al., 2008) or simulated competition (Gill et al., 2006; Rowsell et al., 2009). Central to this research design was replicating the intensity and duration of a 'game-sport match', without compromising consistency of exercise within and between trials. This required evaluation of relative measures of exercise intensity and performance.

The Loughborough Intermittent Shuttle Test (LIST) is a field test which simulates the activity pattern of soccer, also providing a controlled exercise framework within which to evaluate the effect of an intervention (Nicholas, Nuttall & Williams, 2000). It has been shown to induce consistent responses in heart rate, perceived exertion, blood glucose concentration, blood lactate concentration and sprint times (Nicholas et al., 2000) and CK (Thompson et al., 1999; Thompson, Williams, Garcia-Roves, McGregor, McArdle & Jackson, 2003).

On the same indoor sports surface, participants completed the LIST which consists of 90 minutes of 20 metre shuttle running at intermittent speeds. The LIST is broken down into 6x15 minute repeated cycles, interspersed with 3 minutes of rest. Figure 4.4 is a schematic illustration of the LIST.

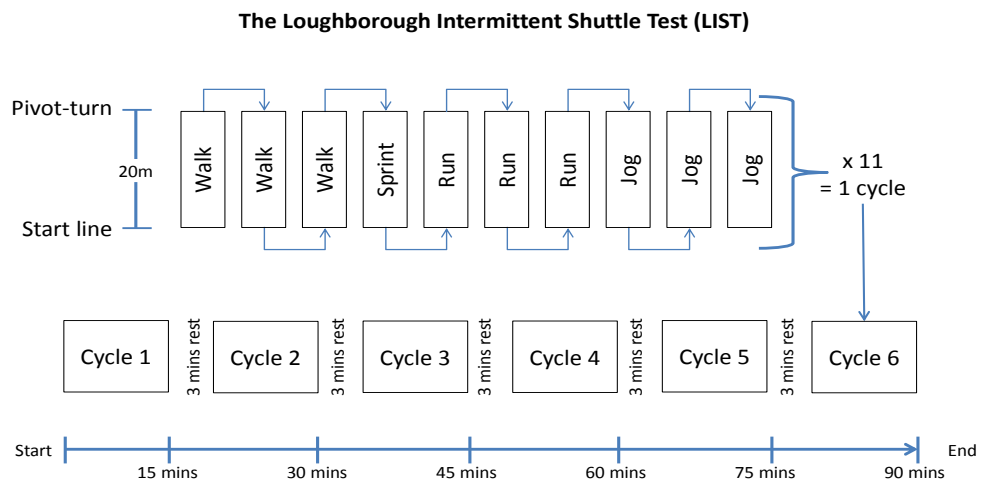


Figure 4.4 Schematic representation of The Loughborough Intermittent Shuttle Test (LIST)

The Loughborough Intermittent Shuttle Test (LIST) consists of 90 minutes of 20 metre shuttle running at intermittent speeds. The LIST is broken down into 6x15 minute repeated cycles, interspersed with 3 minutes of rest. One shuttle speed sequence; repeated 11 times = 1 LIST cycle. Participants followed an audio signal on a specifically recorded CD, indicating when to turn for each shuttle. This thereby dictated the running and walking speeds, at a speed calculated for a VO_2max of $50.2\text{mL.Kg.min}^{-1}$ (15minutes, 27 seconds per cycle).

A specifically recorded CD, using Windows Sound Recorder (Microsoft), dictated performance of the LIST. Participants followed an audio signal indicating when to turn for each shuttle, which thereby dictated the running and walking speeds and does not allow participants to slow down or vary their speed. A lower pitched signal (chord) accompanied by a voice command informed participants when to change the paced locomotor activity and a high pitched (ding) guided participants that they should be half way (10m) along the shuttle (20m). Researchers also advised participants of each shuttle activity and provided encouragement.

Based on preliminary testing data (VO_2max mean $52.2 \pm 4.2 \text{ mL.kg}^{-1}.\text{min}^{-1}$), all participants completed the LIST at a speed calculated for a VO_2max of $50.2 \text{ mL.Kg.min}^{-1}$ (15minutes, 27 seconds per cycle). This ensured a fixed exercise challenge.

Although the LIST exercise intensity pattern is predictable with a predetermined shuttle pace, voluntary effort and performance could vary between trials. Preliminary familiarisation, measures of perceived exertion and sprint performance during the LIST aimed to increase the likelihood that subjects were prepared for the exercise demands, pace appropriately and therefore perform the LIST consistently.

4.6.2.1 LIST Performance

Since effects of the LIST have mainly been reported in untrained subjects (Thompson et al., 2003), it was relevant to appraise and report the effects of the LIST in these trained and familiarised subjects.

15m sprint performance

Within the 20 metre sprint shuttle, 15 metre sprint performance was measured using photocell timing gates (Newtest Powertiming System, Finland). This enabled sprint effort and sprint performance to be monitored within and between trials. Figure 4.5 shows the decline in sprint performance over LIST sub-cycles 1-6 in Trial 1, Trial 2 and Trial 3.

The between trial equivalency of 15m sprint times was evaluated using the statistical package SPSS for Windows (version 16.0, SPSS inc., Chicago, IL, USA). The log transform of the data was used as they showed less heteroscedasticity. ANOVA (2x3) of LIST cycles 1 and 6 revealed a significant main effect for time ($p=0.003$) with no significant difference between trials ($p=0.33$). Subsequent t-tests confirmed 15 metre sprint times were significantly different between the first and sixth cycle of the LIST in each Trial ($p<0.05$). There was a steady increasing trend in mean sprint times across the LIST, with the last cycle being significantly slower than the first cycle in each trial. This suggested a gradual decline in performance which was well established by conclusion of the exercise bout. Physiological, functional and perceived indices of the post-exercise response are discussed in subsequent chapters.

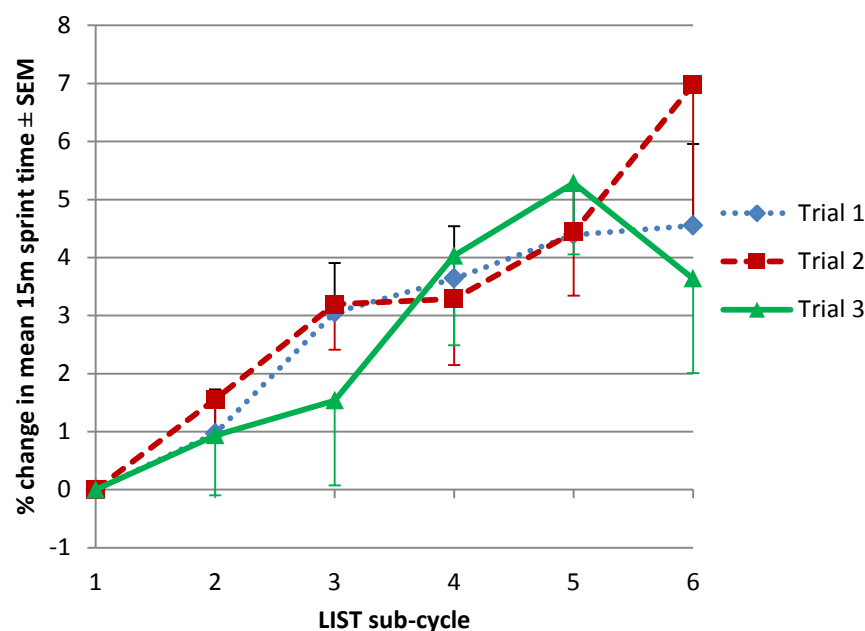


Figure 4.5 Percentage change in mean 15m sprint time for each of the 6 LIST sub-cycles for Trial 1, Trial 2 & Trial 3
The mean \pm SEM percentage change in Loughborough Intermittent Shuttle Test (LIST) 15m sprint time for each of the 6 LIST sub-cycles is shown, for Trial 1 (---◇---dotted line; diamond markers), Trial 2 (- - ■ - - dashed line; square markers) and Trial 3 (-▲-unbroken line; triangle markers).

Rating of Perceived Exertion (RPE)

In the rest period between LIST sub-cycles 5 and 6, participants indicated their Rating of Perceived Exertion (RPE) on a visual analogue scale of 6-20. This was to monitor consistency of effort and fatigue between trials. RPE is a valid indicator of impending fatigue (ACSM, 2006; Borg, 1998). Table 4.2 contains the RPE for Trial 1, Trial 2 & Trial 3.

Table 4.2 LIST Rating of Perceived Exertion (RPE) for Trial 1, Trial 2 and Trial 3

The range, mean \pm standard deviation (SD) of Rating of Perceived Exertion (RPE) between Loughborough Intermittent Shuttle Test (LIST) sub-cycles 5 & 6 are shown for Trial 1, Trial 2 & Trial 3.

Trial	RPE	
	Range	Mean \pm SD
1	13-17	15 \pm 1
2	12-16	14 \pm 2
3	8-17	14 \pm 3

The mean RPE of 14-15 indicated subjective rating of “hard” (ACSM, 2006; Borg, 1998) between the fifth and sixth LIST cycles. The between trial equivalency was evaluated using the statistical package SPSS for Windows (version 16.0, SPSS inc., Chicago, IL, USA). The log transform of the data was used as they showed less heteroscedasticity. ANOVA (3x2) revealed no significant difference in RPE between trials ($p=0.352$).

Summary of LIST performance

Following one familiarisation and 3 test trials separated by a minimum of 7 and maximum of 14 days, RPE and 15m LIST sprint performance did not indicate a trial order effect. (Furthermore, a trial order effect was not observed in any outcome measures, which is further evaluated and discussed in Chapter 5, Chapter 6 & Chapter 7.) Sprint performance was equivalent across trials and had declined significantly by the end of the LIST, indicating fatigue-impaired performance. Larger responses to the first bout were not evident and equivalency of subsequent trials was established. This suggests the cross over design study was conducted over an appropriate timeframe to produce reliable results and the LIST provided a suitable exercise platform upon which to evaluate recovery.

4.6.3 Intervention

Upon completion of the LIST and Post-Exercise outcome measures, participants walked (the consistent distance) to the hydrotherapy suite. For hygiene reasons subjects were required to change into bathing costumes and shower. Shower time was controlled to a maximum of one minute. It was only feasible to standardise shower temperature as “warm”; predetermined by the facility-installed single tap mechanism.

In a random counterbalanced order participants completed trials of:

Cold: 5 minutes of cold water immersion at 8-9°C (mean 8.8±0.3)

Warm: 5 minutes of warm water immersion at 32-37°C (mean 35.1±1.8)

Rest: 5 minutes of passive rest, sitting on a chair (ambient temperature 28-30°C)

Participants were advised of the intervention at the point immediately preceding entering either cold water, warm water or sitting on the chair. Thus, participants were blinded to the intervention sequence in Trials 1 and 2, although could not logically be blinded to the intervention for Trial 3. Table 4.3 contains the randomised counterbalanced water immersion intervention sequence over the 3 trials.

Table 4.3 Randomised counterbalanced intervention sequence

In the randomised cross-over design, intervention sequences of cold water immersion (cold), warm water immersion (warm) and rest; and the number of participants (*n*) completing each sequence over Trial 1, Trial 2 and Trial 3 are shown.

	Trial 1	Trial 2	Trial 3	<i>n</i>
Sequence	cold	warm	rest	<i>n</i> =2
	warm	rest	cold	<i>n</i> =2
	rest	cold	warm	<i>n</i> =2
	cold	rest	warm	<i>n</i> =2
	warm	cold	rest	<i>n</i> =1
	rest	warm	cold	<i>n</i> =2

Intervention conditions were considered consistent on each occasion. Cold water immersion was defined as 8°C-9°C and warm water immersion was defined as 32°C-37°C. The ambient temperature of the hydrotherapy suite was maintained between 28°C-30°C. Table 4.4 contains the mean and range of water immersion intervention temperatures during the study.

Table 4.4 Intervention ambient and water temperatures ($^{\circ}\text{C}$)

The mean \pm standard deviation (SD) and range of intervention water immersion temperatures throughout the trial are shown in degrees Celcius. Cold water immersion was defined as 8°C - 9°C and warm water immersion was defined as 32°C - 37°C .

	Cold	Warm	Rest
Mean \pm SD	8.8 ± 0.3	35.1 ± 1.8	Ambient
Range	8 – 9	32 – 37	28-30

4.6.4 Post intervention recovery monitoring

Between the intervention and 4 hour measurement time-points, participants either remained in the laboratory or carried out non-physical activities in close proximity to the laboratory. Attendance to regular lectures and non-physical workplace activities at the University of Bath were permitted. All participants consumed specified meals and individual nutrition and activity patterns were repeated in each of the trials. Following the 4 hour post-exercise measures, participants were then free to leave the laboratory and were specifically instructed not to engage in any activity that could influence recovery (e.g. wearing compression garments), prior to returning to the laboratory for the 24 hour measurement time-point. Strenuous activity or activity involving water immersion was also not permitted. This completed the trial conditions.

Instructions encompassing dietary intake and activity levels were designed to maximise homeostasis prior to testing as it is well established that nutrition and hydration can influence recovery (Venkatraman & Pendergast, 2002). In this study, it was not feasible to provide participants with standardised meals or strictly confine them to the laboratory. Although recovery was not evaluated using direct measures of metabolism, participants were required to consume the same food and drink at the same times over the preceding 24 hours and 24 hours of test trials (total 48 hours), and specifically during the LIST. This was important for the reliability of post-exercise and early recovery measures.

Participants accurately completed a 'Nutrition and Hydration Log' and an 'Activity Log' which entailed a description of type, quantity and time of dietary intake and activity. Participants then repeated activity, nutrition and hydration intake on each subsequent trial occasion. Participants were asked to record any deviations between trials and were questioned about compliance upon arrival at the laboratory prior to further testing. No meaningful deviations between trials were reported.

4.7 Data management

Upon collection, data were immediately logged onto pre-prepared spread-sheets. Computerised dynamometry and force-plate data were electronically logged. Data were managed according to the established code of medical recording. Subjects were anonymised with reference numbers. Computers were password protected and accessible only by authorised personnel.

Results were reported as mean \pm standard error of measurement (SEM) unless specified otherwise. To minimise variance and facilitate comparison between variables the log transform or percentage change from baseline on each trial occasion was calculated and utilised for further analysis. Statistics describing a percentage change are less affected by the range of measurements and can facilitate comparison between different outcome measures and populations (Atkinson & Nevill, 1998) which can be of greater relevance to sport science practice than evaluation of raw scores (Hopkins, 2000a). As several outcome measures had clearly defined 'normal' and expected post-exercise ranges, absolute values were also reported where relevant.

4.8 Data analysis

4.8.1 Statistical approach

Outcome measures were evaluated for trial order and intervention effects using the statistical package SPSS for Windows (version 16.0, SPSS inc., Chicago, IL, USA). Data were scrutinised for normality and log transform or percentage change data were used for analysis as indicated.

Data were first analysed for a trial order effect irrespective of treatment to determine that the familiarisation process was effective in avoiding a potential excessive response to the exercise bout in the first trial, and ensure the absence of cumulative fatigue or improvement across the three trials. A two way general linear model for repeated measures analysis of variance (ANOVA Trial x Time) was used to identify statistical effects over Pre-Exercise and Post-Exercise levels of time. The Greenhouse-Geisser correction was applied for epsilon <0.75 and the Huynh-Feldt correction for less severe asphericity, with the significance level set at .05. There was no trial order effect for any variable.

Data were then analysed for intervention effects. A two way general linear model for repeated measures analysis of variance (ANOVA Treatment x Time) was used to identify statistical effects of intervention over post-intervention levels of time: 2 hours (with the exception of circulating markers of muscle damage), 4 hours and 24 hours (3x3 or 2x3). The Greenhouse-Geisser correction was applied for epsilon <0.75 and the Huynh-Feldt correction for less severe asphericity. The significance level was set at .05.

As described by Atkinson (2002), where the omnibus hypothesis test was significant for intervention, pre-planned t-tests between level means of treatment were conducted. Pairwise comparisons were between the control condition of rest and water immersion to explore potential effects of water immersion; and between cold and warm water immersion to differentiate potential effects of temperature. To control the type 1 error and preserve optimum power, the Ryan-Holm-Bonferroni procedure for multiple comparisons was applied. Figure 4.6 provides a schematic representation of the statistical approach to data analysis and pre-planned contrasts.

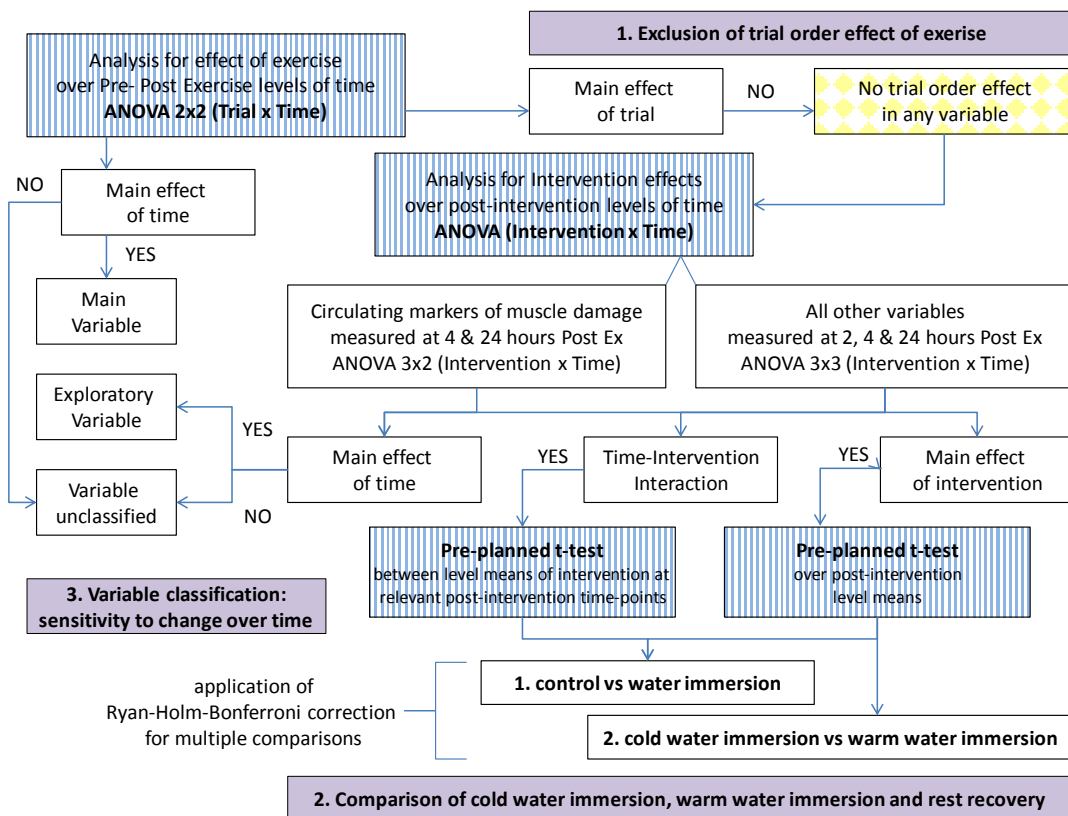


Figure 4.6 Schematic representation of the statistical approach to data analysis

Data were first analysed for a trial order effect. Data were then analysed for intervention effects. As described by Atkinson (2002), where the omnibus hypothesis test was significant for intervention, pre-planned t-tests between level means of treatment were conducted to explore potential effects of water immersion; and differentiate potential effects of temperature. To control the type 1 error and preserve optimum power, the Ryan-Holm-Bonferroni procedure for multiple comparisons was applied. The significance level was set at .05. Variables were also classified according to their sensitivity to change over time, as attributing change in a dependent variable to an intervention is difficult unless the variable changes over time without intervention (Atkinson, 2002).

4.8.2 Justification for statistical approach & management of multiple comparisons

Evaluation of recovery using a spectrum of variables and several post-exercise time-points were strengths of this study (Chapter 8) although analysis consequently generated a large number of multiple comparisons. To manage the Type 1 error rate while preserving statistical power at the level of the variable, comparisons consistent with the hypothesis were pre-planned. At a project level, and in response to research question *iv Of the spectrum of outcome measures, which are the most valued in informing practice decisions*, variables sensitive to post-exercise change and change over time were identified as main and exploratory variables.

Pre-planned comparisons

Comparison of recovery between three levels of intervention (2 x treatment groups and a control group) over several post-exercise time-points presented challenges in managing the Type 1 error rate over multiple comparisons and preserving statistical power to identify

potential small intervention effects. To address this, comparisons consistent with the hypothesis were pre-planned.

Analysis for a trial order effect was pre-planned to Pre-Exercise and Post-Exercise levels of time. Although it were possible that recovery could become acclimatised, post-intervention levels of time were not included as they followed the application of three different interventions and the primary intention was to exclude a trial order effect of exercise. Establishing the significance of Post-Exercise changes was also relevant in evaluating the effect of an intervention on recovery.

Analysis for intervention effects were pre-planned to post-intervention levels of time, as difference between groups was not anticipated prior to administration of the intervention. Albeit, pre-planned comparisons were necessary at every post-intervention time-point as athletes might be expected to participate in subsequent exercise at each of these time-points. The Ryan-Holm-Bonferroni procedure for multiple comparisons aimed to avoided inflation of the type 1 error rate, however this could have increased the type 2 error rate.

Classification of main and exploratory variables

The classification of main variables and exploratory variables was an approach intended to differentiate the most reliable and valid outcome measures from a relatively large spectrum.

The statistical approach of pre-planned pairwise t-tests to compare post-intervention level means in all variables could have been exclusively applied. However, attributing change in a dependent variable to an intervention is difficult unless the variable changes over time without intervention (Atkinson, 2002). Therefore in the approach advocated by Atkinson (2002), an omnibus general linear model (GLM) was first applied to identify main effects of time and intervention across multiple levels. Pairwise comparisons following the omnibus hypothesis test were only planned for variables with significant main effects of intervention *and* change over time ($p \leq .05$); that is variables with significant post-exercise change ($p \leq .05$) and / or main effect of time in the post-intervention time-course. (Table 9.1 presents the ultimate classification of variables in relation to their sensitivity to change over time.)

Exploratory comparisons

The expected post-exercise response and recovery of several variables in this study was unknown. In response to research question 1 “What is the expected time-course of recovery (return to pre-exercise levels) without intervention”, where there was significant post-exercise change and no effect of intervention, pre-planned paired t-tests were conducted between Pre-Exercise and selected post-intervention levels of time (2 hours, 4 hours and 24 hours) in the control condition of rest. To control the type 1 error and preserve optimum power, the Ryan-Holm-Bonferroni procedure for multiple comparisons was applied.

Scatterplots and Pearson’s correlation co-efficient were used to analyse the relationship between selected variables.

Chapter 5 THE EFFECT OF WATER IMMERSION ON CIRCULATING MARKERS OF MUSCLE DAMAGE

5.1 Introduction

This chapter presents and discusses the results specific to circulating markers of recovery. This relates to the outcome measures of creatine kinase (CK), myoglobin, leukocytes, neutrophils and lymphocytes. Post-exercise elevation of leukocytes, neutrophils and lymphocytes were expected (Blannin, 2006; Gleeson, 2007) alongside release of CK and myoglobin which are commonly measured indicators of exercise induced muscle damage (Warren et al., 1999). The expected cascade response following LIST-induced muscle damage was presented by Figure 2.1 Key events following exercise induced muscle damage.

Several studies have concluded that water immersion has no effect on post-exercise CK and myoglobin activity (Ingram et al., 2009; Rowsell et al., 2009; Sellwood et al., 2007), while others have reported benefits compared to passive recovery (Banfi et al., 2007; Gill et al., 2006). In untrained subjects Bailey et al., (2007) showed no change in CK, but decreased myoglobin peak one hour following a LIST protocol and 5⁰C cold water immersion. Conversely, Vaile et al., (2008) observed no change in myoglobin but significant reductions in CK activity 24 and 72 hours post exercise following cold water immersion at 15⁰C and at 48 hours following warm water immersion at 38⁰C. These latter studies utilised immersion times of 10 minutes and 14 minutes respectively. Suzuki et al., (2004) showed no effect on neutrophil count of a one hour water based active recovery session post rugby match. Similarly, short duration extreme-cold air exposures (30 seconds to 2 minutes at -60⁰C to -110⁰C) had no effect on leukocyte levels in athletes (Banfi, Krajewska & Patacchini, 2008). It is unknown whether similar observations would follow shorter immersion duration of 5 minutes.

It was hypothesised that cold and warm water immersions facilitate recovery of circulating markers of muscle damage compared to passive recovery. Hydrostatic pressure-induced blood volume centralisation, increased tissue perfusion and stabilised sympathetic tone following water immersion (McAuley, 2001; Pendergast & Lundgren, 2009) could facilitate the distribution to a pre-exercise state. Furthermore, cold-induced vasoconstriction could curb the proliferative inflammatory response and cellular extravasation of muscle damage indicators following cold water immersion (Armstrong, 1990; Kendall & Eston, 2002). Potential mechanisms of effect are discussed fully in Chapter 2, 2.2.3 Potential mechanisms and effects of water immersion on athlete recovery.

5.2 Method

The following variables in venous blood were measured at Pre-Exercise, Post-Exercise, 4 hours and 24 hour time points:

Leukocytes ($\times 10^9.L^{-1}$)

Neutrophils ($\times 10^9.L^{-1}$)

Lymphocytes ($\times 10^9.L^{-1}$)

Creatine Kinase (CK) ($U.L^{-1}$)

Myoglobin (MYO) ($ng.L^{-1}$)

The venepuncture and laboratory methods are described fully in Chapter 4, 4.6.1 Outcome measurement. Leukocytes are white blood cells, of which neutrophils and lymphocytes are sub-populations. Their post-exercise elevation forms part of the proliferative inflammatory response (Clarkson & Hubal, 2002; Gleeson, 2007; Neiman et al., 2004) and neutrophils' particular function is the phagocytosis of damaged cells and debris (St. Pierre Schneider & Tiidus, 2007). Myofibre proteins CK and myoglobin are released following mechanical disruption of sarcomere myofilaments (Warren et al., 1990) and are accepted indicators of muscle damage following exercise (Rodenburg et al., 1993).

5.3 Results

5.3.1 Evaluation of exercise (trial x time)

For Trial 1, Trial 2 and Trial 3, Pre- and Post- Exercise means and mean percentage change in venous markers of muscle damage are contained in Table 5.1.

Table 5.1 Pre- and Post- Exercise means and mean % change in circulating markers of muscle damage for Trials 1, 2 and 3

For Trial 1, Trial 2 and Trial 3, the Pre-Exercise (Pre-Ex) and Post-Exercise (Post-Ex) mean \pm SEM of venous leukocytes, neutrophils, lymphocytes, creatine kinase and myoglobin are shown. The Post-Exercise percentage change for each trial is also shown along with the average percentage change across the three trials.

	Trial 1			Trial 2			Trial 3			Average % change
	Pre-Ex	Post-Ex	% change	Pre-Ex	Post-Ex	% change	Pre-Ex	Post-Ex	% change	
leukocytes ($\times 10^9.L^{-1}$)	5.8 \pm 0.4	7.8 \pm 0.7	40 \pm 15	5.5 \pm 0.5	7.5 \pm 0.9	38 \pm 15	5.7 \pm 0.7	7.7 \pm 1.0	39 \pm 12	39 \pm 14
neutrophils ($\times 10^9.L^{-1}$)	2.8 \pm 0.4	5.1 \pm 0.5	121 \pm 36	2.7 \pm 0.4	5.1 \pm 0.8	102 \pm 32	3.0 \pm 0.6	5.0 \pm 0.8	96 \pm 31	106 \pm 33
lymphocytes ($\times 10^9.L^{-1}$)	1.9 \pm 0.2	1.7 \pm 0.2	-4 \pm 8	1.8 \pm 0.1	1.6 \pm 0.2	-14 \pm 7	1.8 \pm 0.1	1.7 \pm 0.1	-9 \pm 7	-9 \pm 7
creatine kinase ($U.L^{-1}$)	322 \pm 67	657 \pm 170	118 \pm 44	383 \pm 110	623 \pm 166	77 \pm 13	289 \pm 68	470 \pm 110	74 \pm 11	90 \pm 23
myoglobin ($ng.L^{-1}$)	72 \pm 11	585 \pm 219	726 \pm 337	78 \pm 14	316 \pm 83	302 \pm 59	70 \pm 12	290 \pm 80	308 \pm 56	445 \pm 150

Scrutiny of data histograms did not reveal gross deviation from normality although Shapiro-Wilk tests indicated that data were not normally distributed ($p \leq .05$). Logged data were therefore used for statistical analysis. ANOVA (3x2) revealed no significant trial order effect or trial-time interaction for leukocytes, neutrophils, lymphocytes, CK or MYO ($p > .05$). There was a significant main effect of time ($p < .05$) for leukocytes ($p = .02$), neutrophils ($p = .01$), CK ($p < .01$) and MYO ($p = .01$). There was no main effect of time for lymphocytes ($p = .08$).

5.3.2 Evaluation of intervention (intervention x time)

Mean values of circulating markers of muscle damage in trials of cold water immersion, warm water immersion and rest recovery interventions are contained in Table 5.2. Because these are clinical outcome measures actual values are tabulated alongside graphical illustration of the percentage change over time from Pre-Exercise levels in venous leukocytes, Figure 5.1; neutrophils, Figure 5.2; lymphocytes, Figure 5.3; CK, Figure 5.4 and MYO, Figure 5.5.

Table 5.2 Circulating markers of muscle damage following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest

The mean \pm SEM of venous leukocytes, neutrophils, lymphocytes, creatine kinase and myoglobin 4 hours and 24 hours post-exercise following cold water immersion, warm water immersion and rest recovery interventions. To contextualise these level means, the Pre-Exercise (Pre-Ex) and Post-Exercise (Post-Ex) mean \pm SEM prior to intervention are also shown.

	Pre-Ex			Post-Ex			4 hours			24 hours		
	Cold	Warm	Rest	Cold	Warm	Rest	Cold	Warm	Rest	Cold	Warm	Rest
leukocytes ($\times 10^9 \cdot L^{-1}$)	5.2 \pm 0.4	6.3 \pm 0.7	5.5 \pm 0.5	7.1 \pm 0.9	8.0 \pm 0.9	7.8 \pm 0.8	9.7 \pm 0.8	9.4 \pm 0.6	9.5 \pm 0.7	5.2 \pm 0.4	4.8 \pm 0.4	6.0 \pm 0.4
neutrophils ($\times 10^9 \cdot L^{-1}$)	2.7 \pm 0.4	3.2 \pm 0.6	2.7 \pm 0.4	4.8 \pm 0.7	5.3 \pm 0.7	5.2 \pm 0.8	6.6 \pm 0.6	6.2 \pm 0.5	6.1 \pm 0.5	2.9 \pm 0.4	2.5 \pm 0.3	2.9 \pm 0.4
lymphocytes ($\times 10^9 \cdot L^{-1}$)	1.7 \pm 0.1	2.0 \pm 0.2	1.9 \pm 0.2	1.6 \pm 0.2	1.7 \pm 0.1	1.7 \pm 0.2	2.0 \pm 0.2	1.9 \pm 0.2	2.1 \pm 0.2	1.7 \pm 0.1	1.5 \pm 0.2	2.0 \pm 0.1
creatine kinase ($U \cdot L^{-1}$)	298 \pm 81	382 \pm 98	314 \pm 73	609 \pm 179	628 \pm 151	513 \pm 123	836 \pm 281	753 \pm 133	673 \pm 165	873 \pm 262	749 \pm 227	688 \pm 190
myoglobin ($ng \cdot L^{-1}$)	71 \pm 13	78 \pm 12	70 \pm 11	486 \pm 215	351 \pm 78	354 \pm 115	365 \pm 125	298 \pm 91	294 \pm 88	91 \pm 16	87 \pm 16	86 \pm 17

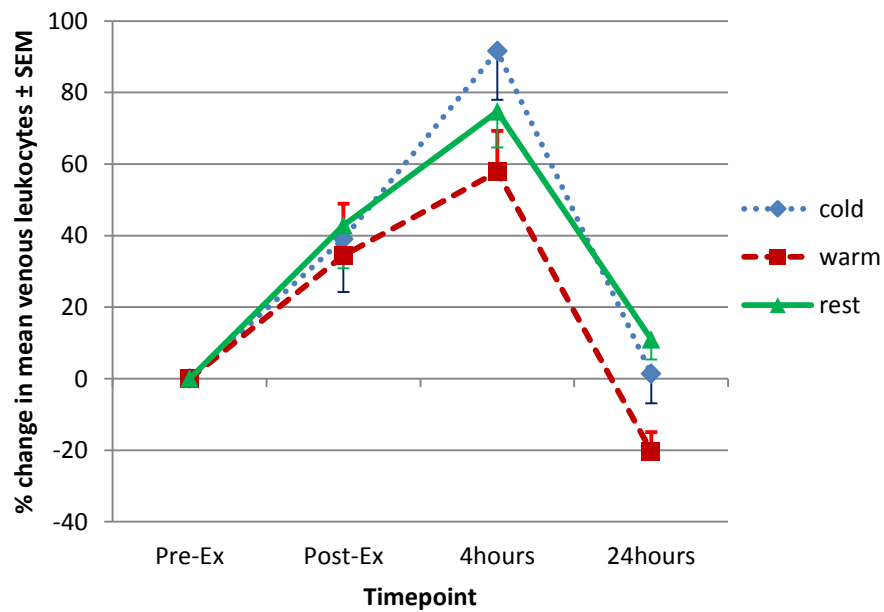


Figure 5.1 Venous leukocytes percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM levels of venous leukocytes for trials involving cold water immersion (---◆---dotted line; diamond markers), warm water immersion (- - ■ - - dashed line; square markers) and rest (-▲-unbroken line; triangle markers), at time-points Post Exercise (Post-Ex) and 4 hours & 24 hours post exercise.

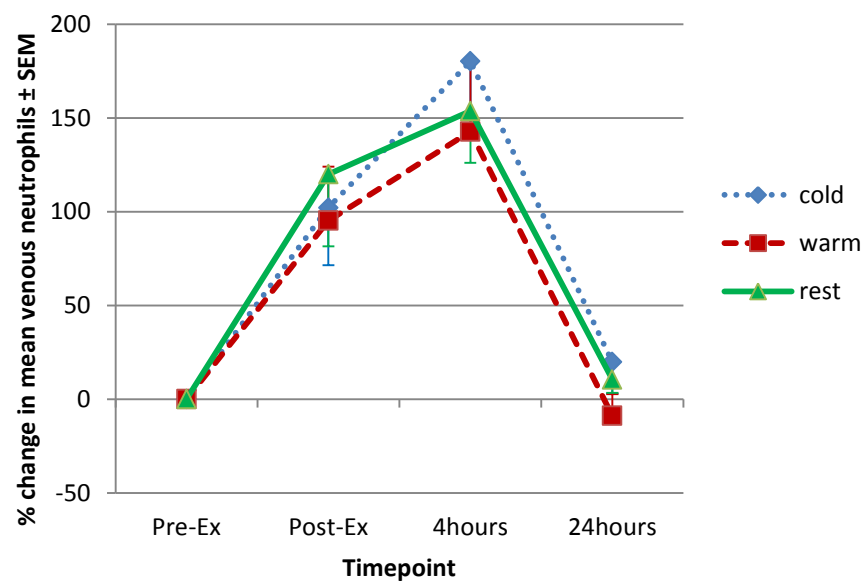


Figure 5.2 Venous neutrophils percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM venous neutrophils for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex) and 4 hours & 24 hours post exercise.

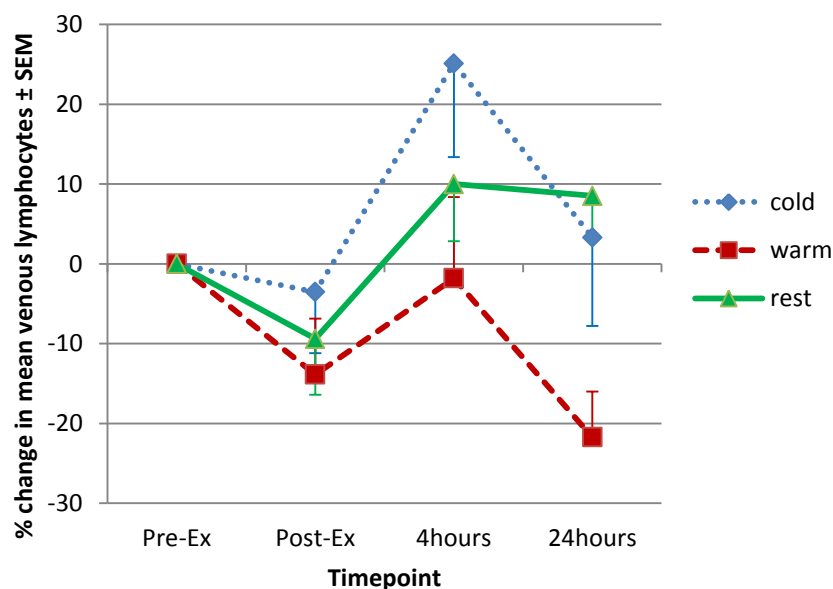


Figure 5.3 Venous lymphocytes percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM venous lymphocytes for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex) and 4 hours & 24 hours post exercise.

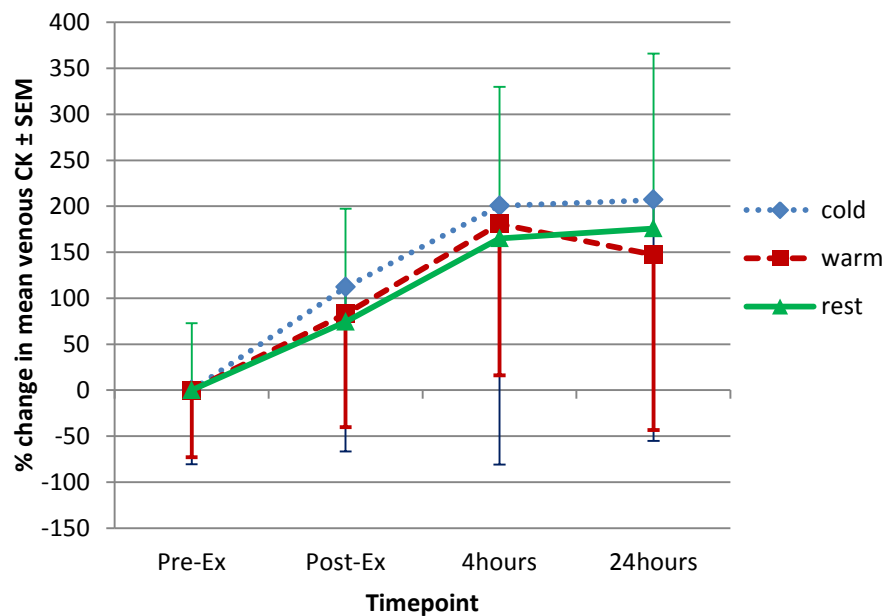


Figure 5.4 Venous creatine kinase percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM venous creatine kinase for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($--\blacksquare--$ dashed line; square markers) and rest ($-\blacktriangle-$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex) and 4 hours & 24 hours post exercise.

Myoglobin timecourse mean \pm SEM

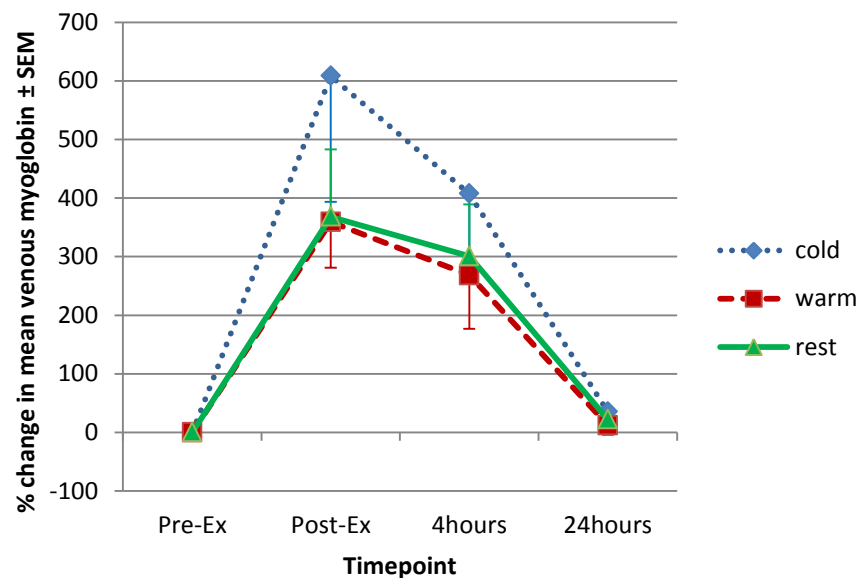


Figure 5.5 Venous myoglobin percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM venous myoglobin for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($--\blacksquare--$ dashed line; square markers) and rest ($-\blacktriangle-$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex) and 4 hours & 24 hours post exercise.

Scrutiny of data histograms did not reveal gross deviation from normality although Shapiro-Wilk tests indicated that data were not normally distributed ($p \leq .05$). Logged data were therefore used for analysis. ANOVA (3x2; treatment x post-intervention levels of time) revealed a significant main effect of time for leukocytes, neutrophils, lymphocytes and MYO ($p \leq .01$). There was not a main effect of time for CK ($p > .05$). There was not a significant effect of intervention for neutrophils, CK or MYO ($p > .05$).

There was a significant time-intervention interaction for leukocytes ($p = .04$). Pre-planned paired t-tests compared intervention level means of water immersion (WI) versus rest (control) and cold water immersion (cold) versus warm water immersion (warm) at 4 and 24 hour post-exercise time-points. The observation of decreased leukocytes at 24 hours following water immersion compared with the control condition of rest was not significant with correction for multiple comparisons (uncorrected $p = .05$; Corrected $p = .20$). There was not a significant difference between cold and warm water immersion ($p > .05$). (Refer Figure 5.1 Venous leukocytes percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions.) The Ryan-Holm-Bonferroni procedure for multiple comparisons for leukocytes is presented in Table 5.3.

Table 5.3 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for venous leukocytes, following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest

Pre-planned paired t-tests compared intervention level means of water immersion (WI) versus rest (control) and cold water immersion (cold) versus warm water immersion (warm) at post-intervention levels of time. The corrected p value (P_{BON}) is given by $m \times p$; where p is the uncorrected p value and m is the total number of comparisons made amongst factor levels (Atkinson, 2002).

Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for leukocytes			
Comparison of level means	Uncorrected p value	value of m in Bonferroni correction	corrected p value (P_{BON})
WI vs control at 24 hours	0.05	4	0.20
cold vs warm at 24 hours	0.39	3	1.17
cold vs warm at 4 hours	0.60	2	1.20
WI vs control at 4 hours	0.93	1	1.20*

* p value found to be smaller than the preceding p value and adjusted to equal the preceding p value

There was a significant main effect of intervention for lymphocytes ($p = .01$). Pre-planned paired t-tests compared intervention level means of water immersion (WI) versus rest (control) and cold water immersion (cold) versus warm water immersion (warm) over post-intervention levels of time. The pattern of decreased lymphocytes following water immersion compared to the control condition of rest (refer Figure 5.3 Venous lymphocytes percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions) was not significant with correction for multiple comparisons (uncorrected $p = .04$; corrected $p = .08$). There was not a significant difference between cold and warm water immersion ($p > .05$). The Ryan-Holm-Bonferroni procedure for multiple comparisons for lymphocytes is presented in Table 5.4.

Table 5.4 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for venous lymphocytes, following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest

Pre-planned paired t-tests compared intervention level means of water immersion (WI) versus rest (control) and cold water immersion (cold) versus warm water immersion (warm) at post-intervention levels of time. The corrected p value (P_{BON}) is given by $m \times p$; where p is the uncorrected p value and m is the total number of comparisons made amongst factor levels (Atkinson, 2002).

Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for lymphocytes			
Comparison of level means	Uncorrected p value	value of m in Bonferroni correction	corrected p value (P_{BON})
WI vs control	0.04	2	0.08
cold vs warm	0.11	1	0.11

5.3.3 Exploratory analysis

In variables with a significant Pre-Post Exercise change and no effect of intervention, the trajectory of return to Pre-Exercise levels was explored. Pre-planned paired t-tests compared neutrophils, CK and MYO Pre-Exercise levels with 4 hours and 24 hours following the control condition of rest. At 4 hours there was a significant difference to Pre-Exercise in neutrophils, CK and MYO ($p < .01$). At 24 hours there was a significant difference to Pre-Exercise in CK ($p = .01$) and no significant difference in neutrophils and MYO ($p > .05$). Application of the Ryan-Holm-Bonferroni correction for multiple comparisons is presented in Table 5.5.

Table 5.5 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons of Pre-Exercise (Pre-Ex) with 4 hours and 24 hour levels of time for venous neutrophils, CK and myoglobin in the control condition of rest

Pre-planned post-hoc paired t-tests compared neutrophils, CK and myoglobin Pre-Exercise (Pre-Ex) with 4 hours and 24 hour levels of time following the control condition of rest. The corrected p value (P_{BON}) is given by $m \times p$; where p is the uncorrected p value and m is the total number of comparisons made amongst factor levels (Atkinson, 2002).

Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons: comparison to Pre-Ex following the control condition "rest"				
variable	comparison of level means	uncorrected p value	value of m in Bonferroni correction	corrected p value (P_{BON})
neutrophils	Pre-Ex vs 4 hours	<0.01	2	<0.01
	Pre-Ex vs 24 hours	0.15	1	0.15
CK	Pre-Ex vs 4 hours	<0.01	2	<0.01
	Pre-Ex vs 24 hours	0.01	1	0.01
myoglobin	Pre-Ex vs 4 hours	<0.01	2	<.01
	Pre-Ex vs 24 hours	0.15	1	0.15

5.4 Discussion

Venous Creatine Kinase (CK) and Myoglobin (MYO)

All Pre-Exercise values of serum CK were within the expected reference limits of 82-1083U/L for male athletes (Mougios, 2007) and the typical rise in serum CK activity which follows skeletal muscle-damaging intense exercise (Brancaccio et al., 2007) was observed. Similar to Ingram et al., (2009) evaluating water immersion recovery, an average 90% CK increase post-exercise was observed. This was followed by further increases of up to 200% at 4 hours post exercise, demonstrating the necessity of several post-exercise time points to construct a representative recovery time-course. Consistent with other exercise studies the myoglobin peak occurred immediately post-exercise (Neubauer et al., 2008; Betts et al., 2009).

There was no significant difference in CK and myoglobin following interventions of cold water immersion, warm water immersion or rest. CK and myoglobin were significantly elevated Post-Exercise and followed the typical post-exercise recovery time-course following the control condition of rest. At 4 hours CK and myoglobin were significantly different to Pre-Exercise and CK remained significantly different to Pre-Exercise at 24 hours. This sustained elevation is likely explained by the half-life of myoglobin and CK rather than prolonged release, however this suggests that recovery to pre-exercise venous levels was incomplete for a subsequent exercise bout on the same-day or next morning.

A threat to the external validity of previous studies is the use of non-athletes to evaluate exercise and recovery interventions, although the typical time-courses observed in this study following rest challenges the belief that trained and familiarised athletes have different recovery capacity to non-athletes. CK activity is expected to peak 1-4 days after exercise (Mougios, 2007) with the peak values occurring within 24 hours post-ironman competition (Neubauer et al., 2008), rugby match (Suzuki et al., 2004) and previous studies conducted in our laboratory using the LIST protocol (Thompson et al., 1999; Thompson et al., 2001). It is possible but unlikely that a post-24 hour intervention effect was missed, as the window of expected peak levels was captured. Furthermore, fatigue and recovery during this post-exercise window is of most interest to athletes' subsequent performance within a 24 hour period.

Exact CK release and clearance rates depend on the type of exercise and level of training (Brancaccio et al., 2007) and variability in recovery has been previously noted in athletes (Mougios, 2007). Although participants were trained and physically comparable in this study, individuality in post-exercise and post-intervention responses is possible. This requires further investigation, and may support the practice of individual profiling and individual recovery regimes in high performance sport. The cross over design and consistent performance of the LIST between trials (see 4.6.2.1 LIST Performance) should have alleviated the influence of individual responses confounding the overall results of this study.

Venous leukocytes

The characteristic venous leukocytosis and neutrophilia during exercise and in the hours following was observed in this study, peaking at 4 hours post exercise. This peak was probably superimposition of the acute and delayed leukocytosis, a phenomenon of prolonged exercise with neutrophilia peaking 2-3 hours post exercise (Blannin, 2006). Although lymphocytosis is typically observed during and immediately post-exercise (Bishop, 2006), a non-significant lymphocytopenia was observed immediately post exercise, with subsequent lymphocytosis at 4 hours.

There was a significant effect of intervention for lymphocytes and a time-intervention interaction for leukocytes, although post hoc comparisons did not have the statistical power to conclude a difference between cold water immersion, warm water immersion and rest. Following warm water immersion the mean leukocyte level at 24 hours was 20% below Pre-Exercise levels, most likely attributable to the 22% lymphocyte reduction. It is possible that water immersion impairs the restoration of venous leukocytes and lymphocytes to resting levels at 24 hours.

Nevertheless, all venous markers of muscle damage were within clinical norms (Provan, Singer, Baglin & Dokal, 2009), rendering the functional implications of these differences speculative. Decreased circulating lymphocytes could create vulnerability to infection (Braun & von Duvillard, 2004) or a decrease in lymphocyte production of immunoglobulins (Gleeson, 2007) which orchestrate the inflammatory response (Kendall & Eston, 2002) and have been linked with overtraining and underperformance conditions (Robson, 2003). This study did not measure these responses and are areas for further research.

Venous neutrophil distribution was not significantly affected by cold or warm water immersion. It is possible that the neutrophil peak fell between measurement time-points in this study, rendering the possibility that an effect of an intervention on the peak was consequently missed. Leukocytosis is greater with higher exercise intensity (Nieman et al., 1994) and is attenuated with training (Blannin et al., 1996) which might increase the difficulty in illuminating potential small effects in this population of trained athletes.

Practice and research implications

Further research is necessary to illuminate the complex process of recovery, including evaluation of direct outcome measures and the implications for sport science and medicine practice. It is an assumption that facilitating return of circulating markers of muscle damage to pre-exercise levels is desirable, although further research is needed to clarify whether this would be beneficial to the athlete, including the underpinning physiological rationale.

For athletes in practice, overarching function is perhaps more crucial than activity at a cellular level. There is considerable redundancy in physiological systems (Braun & von Duvillard, 2004) and changing values may or may not be functionally relevant. It is important to consider cellular function as well as cell count or distribution to understand the functional implications. For example, it is accepted that neutrophil functional capacity is suppressed post intense exercise (Gleeson, 2007; Nieman & Pedersen, 1999) although this is not consistently observed in the literature (Lagranha et al., 2008). St. Pierre Schneider & Tiidus (2007) suggest that

investigation of neutrophil infiltration of skeletal muscle with anti-body staining techniques is required to feasibly and sensitively understand neutrophil role in recovery.

The greatest difference between intervention conditions could have been present at a time point other than 4 and 24 hours post exercise and could have been illuminated by more regular blood samples. This was not feasible within this design but further research could include additional overnight time points.

Inadvertent pre-sample behaviour could have eroded some of the differences between interventions, although subjects lay supine on a plinth for 15 minutes prior to venous blood sampling to counter such effects. Subsequently the Post-Exercise outcome measures were recorded 15 minutes post- rather than immediately post-completion of the exercise protocol. The circulating markers of most interest were not expected to peak immediately post exercise therefore the absence of immediate post exercise measures was not felt to influence the results.

5.5 Chapter summary

All venous markers of muscle damage except lymphocytes were significantly different between Pre- and Post-Exercise, demonstrating that the LIST provided a suitable fatigue protocol upon which to evaluate recovery. There was a main effect of time for lymphocytes in the post-intervention time-course, demonstrating that this variable was also suitably sensitive to change over time for evaluation of intervention effects.

There was no significant effect of cold water immersion or warm water immersion on venous CK, myoglobin and neutrophils. Following the control condition of rest, venous neutrophils, CK and myoglobin remained significantly different to Pre-Exercise levels at 4 hours. Venous CK activity had not recovered to Pre-Exercise levels at 24 hours.

The observed patterns of decreased venous lymphocytes and leukocytes at 24 hours following water immersion, particularly warm water immersion, were not statistically significant. Further research is needed to explore the possibility that water immersion has an effect on circulating leukocytes, particularly the lymphocyte sub-population.

Chapter 6 THE EFFECT OF WATER IMMERSION ON NEUROMUSCULAR FUNCTION

6.1 Introduction

This Chapter presents and discusses the results specific to neuromuscular function indices of recovery. This relates to the outcome measures of maximal isometric voluntary contraction (iMVC) and the performance tests drop jump (DJ) and repeated single leg hop (RH).

Muscle fatigue can be defined as exercise-induced reduction in maximal voluntary muscle force (Gandevia, 2001; Lattier et al., 2004). In the presence of many factors influencing the ability of skeletal muscle to produce power (Fitts, McDonald & Schluter, 1991), muscle function provides an indirect indicator of muscle damage (Clarkson & Hubal, 2002). Evaluating muscle function and dynamic joint stability has been a focus of much injury epidemiology research (Wilkstrom, Tillman, Scenker & Borsa, 2008). Fatigued muscles may fail to produce the protective stabilising responses based on joint proprioception (Rozzi, Yuktanandana, Pincivero & Lephart, 2000) and deterioration from optimal muscle activation results in less efficient movement, influencing athletic performance or the likelihood of injury. Following intense exercise, facilitating the complete recovery of optimal muscle function is therefore desirable prior to engaging in subsequent athletic activities.

Several recent studies have explored the effects of water immersion on the recovery of muscle function. The diverse methodology and results highlight the need for further research to substantiate and inform practice. During a 4 day simulated soccer tournament, Rowsell et al., (2009) showed no effect of 5x60 second cold (10⁰C) or warm (34⁰C) water immersion on next-day countermovement jump performance. Bailey et al., (2007) also concluded that 10 minutes of cold (10⁰C) water immersion had no effect on post-LIST squat jump height. It is possible that the measurement approaches or daily measurement time-points used in these studies were not sufficiently sensitive to detect an effect, as in contrast, Bailey et al., (2007) and Ingram et al., (2009) advocate that cold water immersions of 10 and 15 minutes respectively facilitated the recovery of isometric knee flexion strength over the 48 hours post-exercise. Conversely, Peiffer et al., (2008) showed greater decrements in knee extension following 20 minutes of cold water immersion at 14⁰C compared with passive control, although measurement were only recorded up to 90 minutes post exercise.

Research has also evaluated the effect of water immersion following selectively eccentric exercise protocols (Eston & Peters, 1998; Sellwood et al., 2007; Vaile et al., 2008), although this does not necessarily replicate the fatigue pattern of dynamic athletic performance which is important in applying research findings to practice. Since outcome measures should also evaluate a similar task to the fatiguing exercise (Warren et al., 1999) actual performance evaluation would offer this optimal specificity and validity, but compromise the controlled scrutiny afforded by judiciously designed laboratory neuromuscular testing.

St. Clair Gibson & Noakes (2004) suggest central nervous system (CNS) mediated neuromuscular function is best measured using EMG. However for production of a given force,

there is large same-day and between-day fluctuation in EMG-measured muscle fibre recruitment patterns (Chapter 3). Measurement of functional performance output was therefore considered more appropriate in this study to evaluate a practice-related intervention. This study evaluated the post-exercise response and effect of water immersion on recovery of maximal voluntary muscle force (MVC), jump performance and repeated-hop performance.

Isometric maximal voluntary contraction (MVC) is an accepted reproducible force (Hales & Gandevia, 1988) and is routinely used in muscle function assessment (Bampouras, Reeves, Baltzopoulos & Magnaris, 2006). Lower limb MVC measured using dynamometry has been examined in previous water immersion recovery studies (Bailey et al., 2007; Ingram et al., 2009; Peiffer et al., 2008) and was therefore included in this study for comparison. Similar to athletic performance, drop jump and repeated hop performance utilise lower limb muscle groups in a dynamic fashion while enabling detailed evaluation of force and jump performance characteristics.

Performance sport demands maximum skill performance with efficiency, consistency and minimal injury risks, therefore subsidiary components of the jump and repeated hop skill were thoroughly explored. The drop jump and single leg hop are two of the most widely used measures of lower body functional power (Maulder & Cronin, 2005). Countermovement and squat jump have previously been utilised to evaluate jump mechanics (Bailey et al., 2007; Cormie, McBride & McCauley, 2009; Rowsell et al., 2009), however they do not permit scrutiny of landing and take-off phases during a single contact phase. Furthermore, drop jump technique requires a combination of short contact time and maximum jump height enabling evaluation of performance in dimensions of both time and displacement.

Single leg hop series represent integration of neuromuscular co-ordination, force-producing capability and proprioception (Clark et al., 2002). Single leg tests remove some influence of co-ordination and force contribution associated with double leg measures, with fatigue shown to induce biomechanical changes in single leg hop joint kinematics and muscle activation patterns (Augustsson et al., 2006; Orishimo & Kremenec, 2006). Furthermore, assessment of cyclic and unilateral propulsion is highly specific to many athletic movement patterns (Maulder & Cronin, 2005).

A reduction in force producing capability defines fatigue (Al-Zahrani, Gunasekaran, Callaghan, Gaydecki, Benitez & Oldham, 2008; Gandevia, 2001; Lepers, Theural, Hausswirth & Bernard, 2008; Morton et al., 2005). It was hypothesised that less force would be generated in fatigue, resulting in reduced peak torque production, jump height and hop height. It was also proposed that muscles would be less able to decelerate and accelerate the centre of mass, resulting in greater jump landing phase and contact time. However, it was foreseen that longer contact times could enable generation of the same force albeit over a longer period of time. This raised the concurrent hypothesis that reduced jump height would not be observed, regardless of fatigue-related changes in jump characteristics. Variables that captured both force and time, and characteristics relating to mechanical efficiency were therefore explored.

Jump phases were differentiated as they have inherent mechanical differences and present distinct muscular demands. During the landing phase of a jump, muscles act eccentrically to

counteract the ground reaction force (GRF) vector acting on the centre of mass (CoM). During the take-off phase the muscles act concentrically to accelerate the CoM in the opposite direction, utilising the GRF to generate maximum take-off velocity. The effort required to control the GRF acting on the CoM during the jump conceivably increases as muscles fatigue; which could manifest in altered muscle recruitment patterns, increased energy expenditure or altered technique. With or without a change in jump height, these characteristics could be referred to as descriptors of performance efficiency. The association between injury and jump landing biomechanics is well described (Dufek & Bates, 1991; Steele, 1990), therefore the landing phase of the jump and alterations and recovery of mechanics during this component were of particular interest. Fatigue-altered neuromuscular responses include proprioception, tremor, and postural control (Gandevia, 2001) which could result in decreased consistency and precision in repeated functional skill execution. Increased variability in repeated hop performance and landing locus was therefore hypothesised with fatigue.

6.2 Method

Variables relating to neuromuscular function were measured at Pre-Exercise, Post-Exercise, 2 hours, 4 hours and 24 hour time points. Pre-sample behaviour at each of these time-points was standardised and consistent, and the laboratory methods are described fully in Chapter 4, 4.6.1 Outcome measurement. The following functional actions were evaluated:

Knee Extension (KE) isometric maximum voluntary contraction (MVC)

Knee Flexion (KF) isometric maximum voluntary contraction (MVC)

Drop Jump (DJ)

Repeated Single Leg Hop (RH)

The next section details the definition and calculation of variables relating to neuromuscular function from force plate data. Variables were calculated mathematically using Excel spreadsheets designed specifically for this purpose.

6.2.1 Performance test data management

6.2.1.1 Drop Jump (DJ)

Drop jump technique required a combination of maximum jump height and short contact time and subjects were instructed to jump as high as they could as quickly as possible. Therefore variables accounting for performance in dimensions of displacement and time were selected. *Jump Height* and *ground Contact Time* were direct measures of subjects' performance of the task, alongside more detailed analysis of force characteristics during the eccentric (centre of mass descending) and concentric (centre of mass ascending) phases of contact time. These

variables were of interest to more accurately identify and describe the effects of fatigue and recovery on jump mechanics. As the principal aim of the task was to perform a maximum jump, the trial recording the maximum *Jump Height* was selected for further analysis. The following parameters were calculated for the maximal jump of each participant at each post-exercise time point in each trial:

Jump Height (*m*)

Jump Contact Time (*s*)

Jump Reactive Index (*ratio of contact time to flight time*)

Jump Work (*neg, pos, net, abs*) (J)

Jump Peak Power (*neg, pos*)

6.2.1.2 Force- time curve

The force plate data produced a ground reaction force (GRF)-time history (Figure 6.1). The GRF was defined as F_{net} ; where F_{net} was the sum of force on force plates 1 & 2 at that point in time. $F_{net} > 0$ defined *Contact Time*, between time-points of initial landing (t_L) and take-off (t_{to}), indicating GRF acting on the centre of mass (CoM).

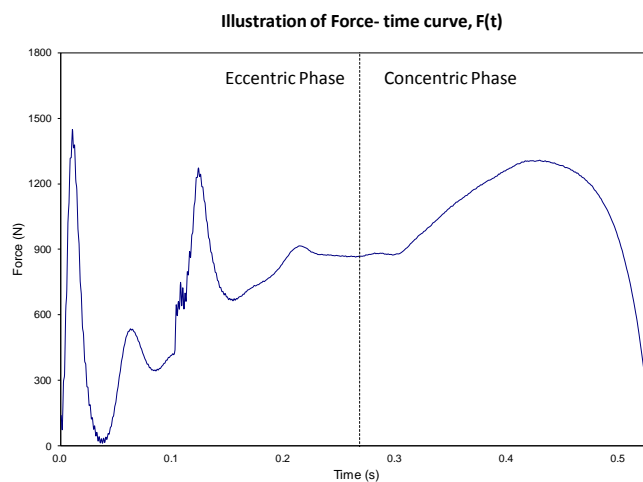


Figure 6.1 Drop Jump Contact Time: illustration of a Ground Reaction Force (GRF)-time (t) curve, $F(t)$

The Ground Reaction Force (GRF; given by Force) during the time of contact (Time), on the force plate during the Drop Jump is illustrated. GRF was defined as the net force plate force (F_{net}); where F_{net} was the sum of force on force plates 1 & 2 at that point in time. Contact Time was from point of landing to point of take-off, given as $F_{net} > 0$ indicating GRF acting on the centre of mass (CoM). Definition of the eccentric and concentric phases of contact time was mathematically determined from the velocity curve: $velocity = 0$ which approximated the time-point where the CoM changed direction from descent (eccentric landing phase) to ascent (concentric take-off phase). (*This figure is a representation of Subject 1, Trial 3, Pre-ex, Jump1.*)

6.2.1.3 Calculation of variables

As the study did not include kinematic measures of displacement, *Jump Height* was calculated mathematically. The kinematic relationship $v = u + at$, where v = velocity at time (t), u = initial velocity, a = acceleration (constant) was applied to the *Flight Time* associated with a jump to calculate take-off velocity (v_{to}) (Equation 1). *Flight Time* was defined between take-off (t_{to}) and the second instance of initial landing, where $F_{net} > 0$ defined contact with the force plate.

$$v = u + at$$

At the top of the jump:

$$\begin{aligned} v(t) &= 0 @ t = \frac{T}{2} \\ \therefore 0 &= u - 9.81 \left(\frac{T}{2} \right) \\ u &= \frac{9.81T}{2} \\ v_{to} &= \frac{9.81T}{2} \end{aligned}$$

Equation 1: Calculation of take-off velocity (v_{to})

where T = total flight time (known), a = acceleration due to gravity = -9.81ms^{-2} .

The kinematic relationship $v = u + at$, where v = velocity at time (t), u = initial velocity, a = acceleration (constant) was applied to the flight time associated with a jump to calculate take off velocity (v_{to}). *Flight time* was defined between take-off (t_{to}) and the second instance of initial landing, where $F_{net} > 0$ defined contact with the force plate.

Similarly, *Jump Height* (x) could have been calculated by integrating $v(t)$ to obtain $x(t)$, where x = vertical displacement from the force plate surface (Equation 2), however this would have introduced a secondary set of integration errors.

$$\begin{aligned} x(t) &= \int v(t) \\ &= \int utat \\ &= ut + \frac{at^2}{2} \\ \text{Since } u &= \frac{9.81T}{2} \\ \therefore x(t) &= \left(\frac{9.81T}{2} \right) t + \frac{at^2}{2} \end{aligned}$$

Equation 2: Calculation of vertical displacement at a given time point ($x(t)$)

where x = vertical displacement, v = velocity, t = time, u = initial velocity, a = acceleration due to gravity = -9.81ms^{-2} , T = total flight time (known).

Jump height (x) could be calculated by integrating the velocity-time curve ($v(t)$) to obtain a vertical displacement-time ($x(t)$) curve. However this would have introduced a secondary set of integration errors.

Therefore *Jump Height* was calculated from the point of maximum displacement which occurred at $t = \frac{T}{2}$, when $v(t) = 0$, indicating the CoM changed direction from ascent to descent, given by Equation 3.

$$\begin{aligned}
x &= \frac{9.81T}{2} \times \frac{T}{2} - \frac{9.81\left(\frac{T}{2}\right)^2}{2} \\
&= \frac{9.81T^2}{4} - \frac{9.81T^2}{8} \\
&= \frac{9.81T^2}{8}
\end{aligned}$$

Equation 3: Calculation of Jump Height from the point of maximum displacement

where x = vertical displacement, v = velocity, t = time,

T = total flight time (known), acceleration due to gravity = -9.81ms^{-2} ,

Jump height (x) was calculated from the point of maximum displacement which occurred at $t = \frac{T}{2}$, when $v(t) = 0$ indicating the CoM changed direction from ascent to descent.

6.2.1.4 Calculation of acceleration-time, velocity-time and power-time curves

An acceleration-time curve, $A(t)$, (Figure 6.2) was generated from the force-time curve ($F(t)$) and a velocity-time curve, $v(t)$, (Figure 6.3) was generated from the integral of the acceleration-time curve. These were calculated according to Equation 4, based on the known time-points of take-off (t_{to}) and landing (t_L); and take-off velocity (v_{to}) as a function of flight time. A power-time curve, $P(t)$, (Figure 6.4) was generated from the force-time and velocity-time curves, according to the relationship Power = Force x Velocity. Definition of the eccentric and concentric phases of contact time was mathematically determined from the velocity curve which allowed estimation of velocity at every time point. Previous to the point of take-off, the time point where $v = 0$ approximated the time-point where the CoM changed direction from descent (eccentric landing phase) to ascent (concentric take-off phase).

$$\begin{aligned}
\frac{F(t)}{mass} &\rightarrow a(t_L^{to}) \\
a &= \frac{dv}{dt} \therefore v = \int_L^{to} a \cdot dt
\end{aligned}$$

Equation 4: Calculation of the acceleration-time curve, $A(t)$, and velocity-time curve, $v(t)$

where F = force plate force, a = acceleration, t = time, v = velocity, L = landing, to = take-off

An acceleration-time curve ($A(t)$) was calculated from the force-time curve ($F(t)$) given by the force plate data trace.

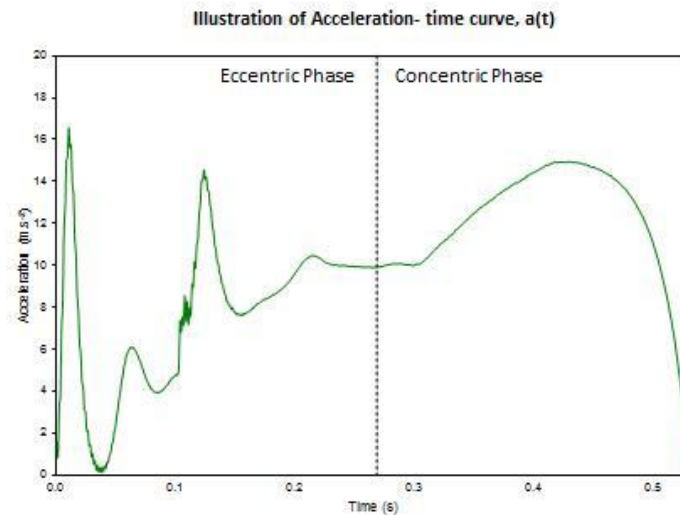


Figure 6.2 Drop Jump Contact Time: illustration of an acceleration-time curve, $a(t)$

An acceleration-time curve, $a(t)$, during the time of contact (Time) on the force plate during the Drop Jump is illustrated. This was calculated from the force-time curve, $F(t)$, given by the force plate data trace. Contact Time was from point of landing to point of take-off, given as $F_{\text{net}} > 0$ indicating ground reaction force (GRF) acting on the centre of mass (CoM). Definition of the eccentric and concentric phases of contact time was mathematically determined from the velocity-time curve, $v(t)$: $\text{velocity} = 0$ which approximated the time-point where the CoM changed direction from descent (eccentric landing phase) to ascent (concentric take-off phase). *(This figure is a representation of Subject 1, Trial 3, Pre-ex, Jump1.)*

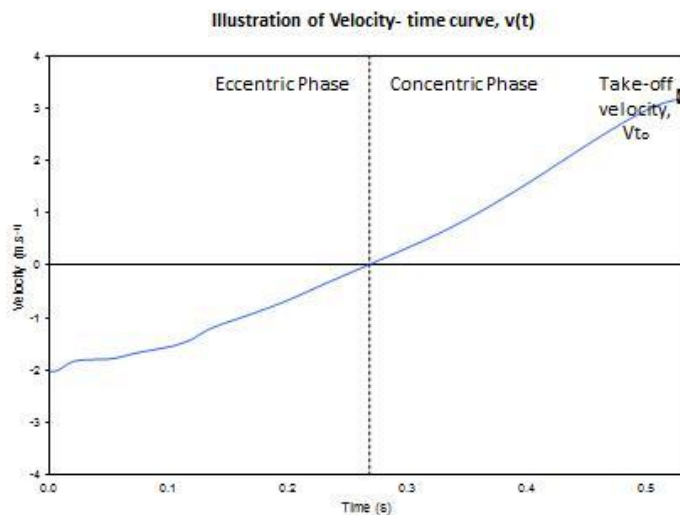


Figure 6.3 Drop Jump Contact Time: illustration of a velocity-time curve, $v(t)$

A velocity-time curve, $v(t)$, during the time of contact (Time) on the force plate during the Drop Jump is illustrated. This was calculated from the integral of the acceleration-time curve, $a(t)$, based on the known take-off velocity (v_{to}) (which is indicated) as a function of flight time. Contact Time was from point of landing to point of take-off, given as $F_{\text{net}} > 0$ indicating ground reaction force (GRF) acting on the centre of mass (CoM). Definition of the eccentric and concentric phases of contact time was mathematically determined from the velocity-time curve, $v(t)$: $\text{velocity} = 0$ which approximated the time-point where the CoM changed direction from descent (eccentric landing phase) to ascent (concentric take-off phase). *(This figure is a representation of Subject 1, Trial 3, Pre-ex, Jump1.)*

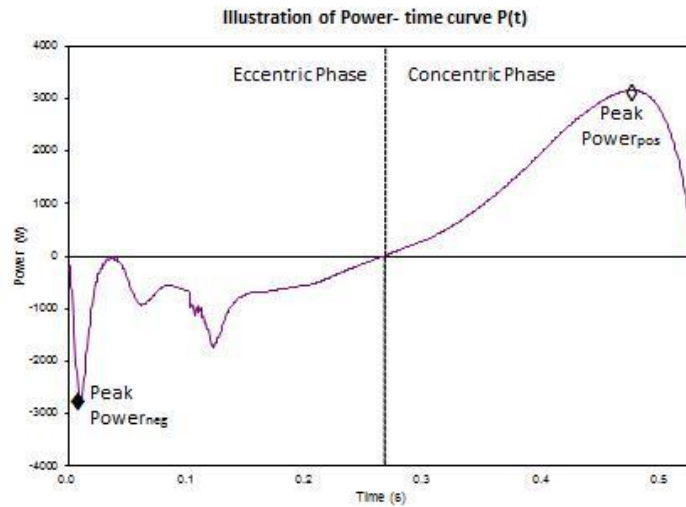


Figure 6.4 Drop Jump Contact Time: illustration of a power-time curve, $P(t)$

A power-time curve, $P(t)$, during the time of contact (Time) on the force plate during the Drop Jump is illustrated. This was generated from the force-time ($F(t)$) and velocity-time, $v(t)$ curves, according to $\text{Power} = \text{Force} \times \text{Velocity}$. Contact Time was from point of landing to point of take-off, given as $F_{\text{net}} > 0$ indicating ground reaction force (GRF) acting on the centre of mass (CoM). Definition of the eccentric and concentric phases of contact time was mathematically determined from the velocity curve: $\text{velocity} = 0$ which approximated the time-point where the CoM changed direction from descent (eccentric landing phase) to ascent (concentric take-off phase). Peak power during the concentric phase (Peak Power_{pos}) and Peak power during the eccentric phase (Peak Power_{neg}) are indicated. (This figure is a representation of Subject 1, Trial 3, Pre-ex, Jump1.)

Identification of Work (net); Work (neg); Work (pos); Work (abs), (J)

Work represented the rate at which a force is applied. It was calculated as function of power and time according to Equation 5 and was given by the area under the Power-time curve, $P(t)$ (Figure 6.5). Work was considered to represent the effort required to control the GRF acting on the CoM during the jump task; an overall representation of demand on the athlete to complete the drop jump for maximum height and rapid contact time.

$$\begin{aligned}
 &\text{Since } P = F \cdot v = F \cdot d \cdot t^{-1} \\
 &\text{and } W = F \cdot d \\
 &\quad W = P \cdot t \\
 &W = P \times \text{contact time} \\
 &\quad = \text{area under } P(t) \\
 &\quad = \int P(t)
 \end{aligned}$$

Equation 5: Calculation of Work

where W = work, P = power, F = force, t = time, v = velocity, d = distance

Work was calculated as function of power and time, and was given by the area under the Power-time curve, $\int P(t)$.

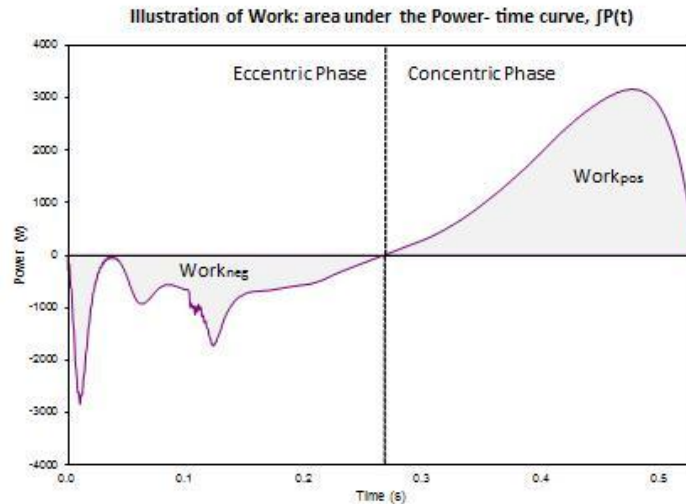


Figure 6.5 Illustration of the relationship of the power-time curve, $P(t)$, to the variable work, $JP(t)$.

Work was calculated as function of power and time, and was given by the area under the power-time curve, $JP(t)$. It was considered to represent the effort required to control the ground reaction force (GRF) acting on the centre of mass (CoM) during the jump task; an overall representation of demand on the athlete to complete the drop jump for maximum height and rapid contact time. Work during the eccentric phase of contact time was defined as negative work (W_{neg}). Work during the concentric phase of contact time was defined as positive work (W_{pos}).

(This figure is a representation of Subject 1, Trial 3, Pre-ex, Jump1.)

The components of work (W) performed during the Drop Jump are presented in Figure 6.6. Work done to counteract the GRF during the eccentric landing phase of contact has negative velocity (W_{neg}). Work done during the concentric contact phase as the GRF is utilised to accelerate the CoM into a propulsive ascent has positive velocity (W_{pos}). (This is in accordance with the convention that velocity acting in the same direction as force is positive, therefore power and hence work is positive.) Mathematically, W_{net} was defined as the sum of W_{neg} and W_{pos} during the eccentric and concentric contact phases of the jump respectively. Net Work (W_{net}) represented the total work applied to the CoM to control the GRF during the contact phase.

While W_{net} represented the gross work performed, it did not represent the total effort required to complete the task as negative and positive work were mathematically counterbalanced. Therefore in addition to the subsidiary variables, Absolute Work (W_{abs}) was also explored. W_{abs} represented total work required to control the GRF acting on the CoM during the jump regardless of the direction in which that work was done. This variable was most representative of the overall force-over-time demand on the athlete to complete the drop jump for maximum height and rapid contact time.

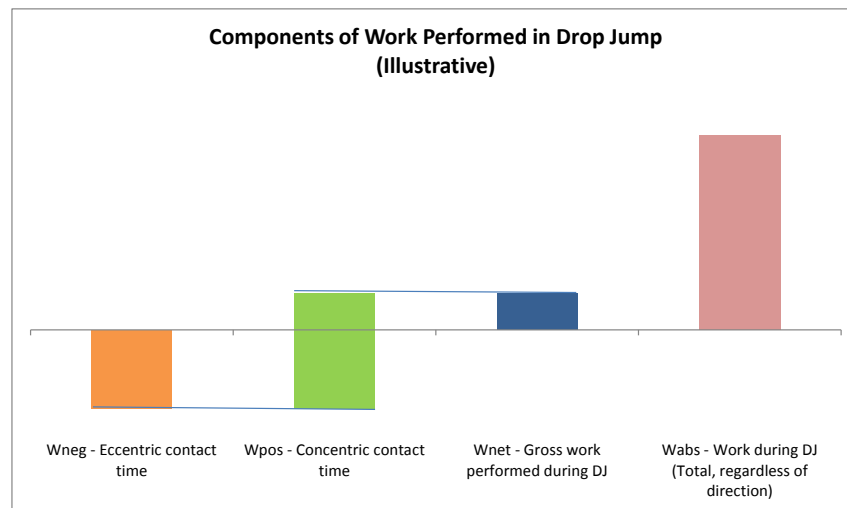


Figure 6.6 Components of work performed during the Drop Jump

Mathematically, net work (W_{net}) was defined as the sum of negative work (W_{neg}) and positive work (W_{pos}) during the eccentric and concentric contact phases of the jump respectively. W_{net} represented the total work applied to the CoM to control the GRF during the contact phase. W_{net} represented the gross work performed, comprising negative and positive work which were mathematically counterbalanced. Absolute work (W_{abs}) represented total work required to control the GRF acting on the CoM during the jump regardless of the direction in which that work was done.

6.2.1.5 Repeated Single Leg Hop (RH)

The repeated single leg hop (RH) sequence required subjects to repeatedly produce maximum height, minimal contact time and maintain a consistent landing locus. It was therefore valid to analyse both vertical and horizontal displacement, consistency and efficiency. The following parameters were calculated for each participant at each time point in each condition:

Hop Height (*total, average of 6 Hops, SD*)

Hop Contact Time (*total, average of 5 contact phases, SD*)

Hop Flight Time (*total, average of 6 flight phases, SD*)

Landing locus displacement (*Displacement*)

Hop Work (*Hop Work_{abs}*)

The average of completed trials was used for analysis, thereby utilising all available data and reduced the influence of outlying values on the overall results. Hop Height, Hop Contact Time, Hop Flight Time and Hop Work were calculated according to the approach previously described for drop jump variables. The hop landing locus was mapped on the Force Plate and Displacement was defined as the total distance travelled in the sequential pathway. Illustration of a sequential hop sequence landing loci and displacement is provided by Figure 6.7.

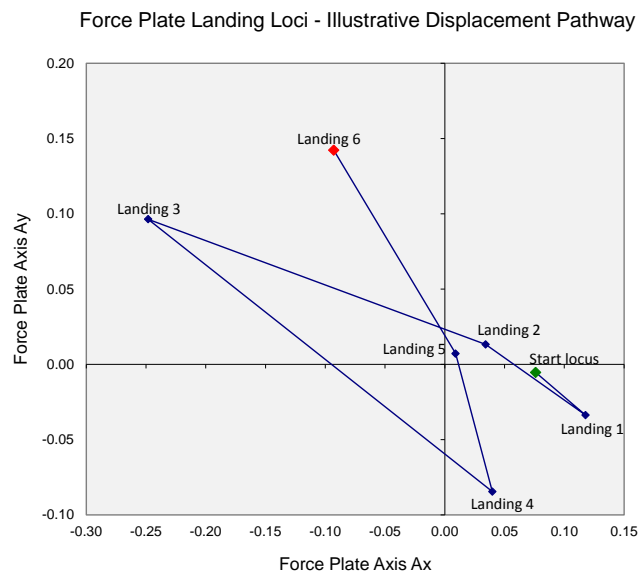


Figure 6.7: Illustration of sequential hop landing loci and displacement

The hop landing locus was mapped on the Force Plate. Displacement was defined as the total distance travelled in the sequential pathway. The Start locus and Landing points of each hop in the sequence are labelled. *(This figure illustrates the data trace of Subject 1, Trial 1, Post Exercise, Hop 1.)*

6.3 Results

6.3.1 Isometric Maximum Voluntary Contraction (MVC)

Evaluation of exercise (trial x time)

For Knee Flexion (KF) Peak Torque and Knee Extension (KE) Peak Torque, ANOVA (2x3) revealed a significant main effect of time ($p < 0.05$) with no significant main effect of trial or time-trial interaction ($p > 0.05$). Change in Pre- and Post-Exercise KF Peak Torque & KE Peak Torques are contained in Table 6.1.

Table 6.1 Percentage change in Pre- and Post-Exercise Knee Flexion (KF) & Knee Extension (KE) peak torque

For Trial 1, Trial 2 and Trial 3, the Pre-Exercise (Pre-Ex) and Post-Exercise (Post-Ex) mean \pm SEM of KF Peak Torque and KE Peak Torque are shown. The Post-Exercise percentage change for each trial is also shown along with the average percentage change across the three trials.

	Trial 1			Trial 2			Trial 3			Average % change
Trial	Pre-Ex	Post-Ex	% change	Pre-Ex	Post-Ex	% change	Pre-Ex	Post-Ex	% change	
KF peak torque (N.m)	139 \pm 36	123 \pm 28	-11 \pm 3	141 \pm 32	120 \pm 30	-15 \pm 3	146 \pm 54	127 \pm 38	-11 \pm 4	-12 \pm 3
KE peak torque (N.m)	257 \pm 17	241 \pm 17	-6 \pm 3	247 \pm 10	239 \pm 13	-3 \pm 4	250 \pm 14	231 \pm 16	-8 \pm 4	-6 \pm 4

Evaluation of intervention (intervention x time)

Scrutiny of percentage change data histograms did not reveal gross deviation from normality and there was no significant difference between the mean and median data (Shapiro-Wilk $p > 0.05$). Table 6.2 contains mean isometric KF Peak Torque and KE Peak Torque (N.m) following trials of cold water immersion, warm water immersion and rest recovery interventions. Because these are clinical outcome measures actual values are tabulated alongside graphical illustration of the percentage change over time from Pre-Exercise levels in KF Peak Torque, Figure 6.8 and KE Peak Torque, Figure 6.9.

Table 6.2 Knee Flexion (KF) Peak Torque and Knee Extension (KE) Peak Torque following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest

The mean \pm SEM of KF Peak Torque and KE Peak Torque following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest at 2, 4 hours and 24 hours post exercise.

	2 hours			4 hours			24 hours		
	Cold	Warm	Rest	Cold	Warm	Rest	Cold	Warm	Rest
KF peak torque (N.m)	134 \pm 13	123 \pm 11	123 \pm 7	143 \pm 16	117 \pm 11	121 \pm 10	143 \pm 19	112 \pm 8	120 \pm 10
KE peak torque (N.m)	233 \pm 16	241 \pm 14	255 \pm 9	240 \pm 21	243 \pm 11	246 \pm 9	232 \pm 19	255 \pm 15	236 \pm 8

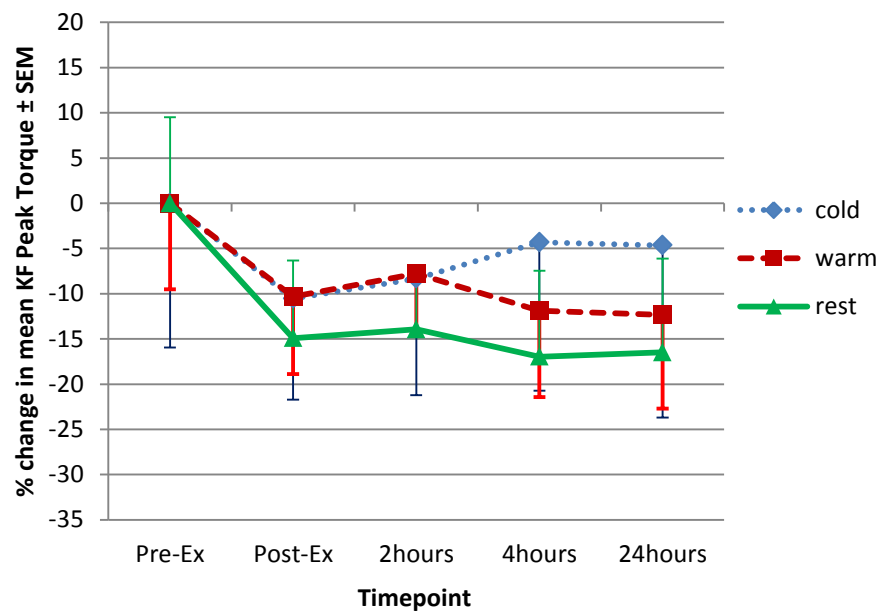


Figure 6.8 Knee Flexion (KF) Peak Torque percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM KF Peak Torque for trials involving cold water immersion (\cdots — \diamond —dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

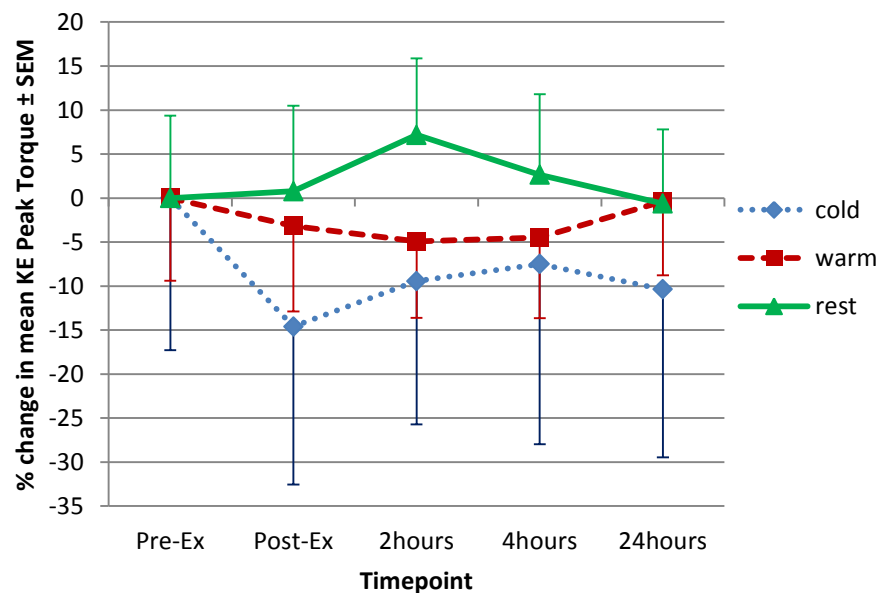


Figure 6.9 Knee Extension (KE) Peak Torque percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM KE Peak Torque for trials involving cold water immersion (\cdots — \diamond —dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

For KF Peak Torque ANOVA (3x3) revealed a significant main effect for time ($p<.01$), with no significant main effect of intervention or time-intervention interaction ($p>0.05$). For KE Peak Torque ANOVA (3x3) revealed no significant main effect for time, and a significant effect of intervention ($p=0.01$). Significantly lower KE Peak Torque followed water immersion compared with the control condition of rest ($p<.01$), and lower KE Peak Torque followed cold water immersion compared with warm water immersion ($p=.01$). Table 6.3 presents the Ryan-Holm-Bonferroni procedure for multiple comparisons for KE Peak Torque.

Table 6.3 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for Knee Extension (KE) Peak Torque, following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest

Pre-planned paired t-tests compared intervention level means of water immersion (WI) versus rest (control) and cold water immersion (cold) versus warm water immersion (warm) at post-intervention levels of time. The corrected p value (P_{BON}) is given by $m \times p$; where p is the uncorrected p value and m is the total number of comparisons made amongst factor levels (Atkinson, 2002).

Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons for KE Peak Torque			
Comparison of level means	Uncorrected p value	value of m in Bonferroni correction	corrected p value (P_{BON})
WI vs control	<0.01	2	<0.01
cold vs warm	0.01	1	0.01

6.3.2 Drop Jump (DJ)

Evaluation of exercise (trial x time)

For all DJ variables ANOVA (2x3) revealed no significant effect for trial or time-trial interaction ($p>0.05$). There was a significant main effect of time for the variables of Jump Work_{neg} ($p<0.01$), Jump Work_{abs} ($p<0.01$) and Jump Peak Power_{neg} ($p=0.04$). Change in Pre- and Post-Exercise means for Trials 1, 2 and 3 and mean percentage change in DJ variables are contained in Table 6.4.

Table 6.4 Drop Jump variables: Pre- and Post- Exercise means for Trials 1, 2 and 3 and mean % change

For Trial 1, Trial 2 and Trial 3, the Pre-Exercise (Pre-Ex) and Post-Exercise (Post-Ex) mean \pm SEM of Drop Jump variables are shown, along with the average percentage change across the three trials.

	Trial 1		Trial 2		Trial 3		Av % change
	Pre-Ex	Post-Ex	Pre-Ex	Post-Ex	Pre-Ex	Post-Ex	
Jump Height (m)	0.45 \pm 0.02	0.43 \pm 0.02	0.43 \pm 0.02	0.43 \pm 0.02	0.44 \pm 0.02	0.42 \pm 0.02	-2 \pm 3
Jump Flight Time (s)	0.60 \pm 0.02	0.59 \pm 0.01	0.59 \pm 0.01	0.59 \pm 0.01	0.60 \pm 0.01	0.58 \pm 0.02	-2 \pm 2
Jump Contact Time (s)	0.48 \pm 0.05	0.48 \pm 0.04	0.46 \pm 0.05	0.48 \pm 0.05	0.49 \pm 0.05	0.49 \pm 0.06	3 \pm 4
Reactive Index	1.5 \pm 0.2	1.4 \pm 0.2	1.6 \pm 0.3	1.5 \pm 0.2	1.5 \pm 0.3	1.5 \pm 0.3	-2 \pm 4
Jump Work net (J)	94 \pm 106	105 \pm 98	81 \pm 54	160 \pm 118	105 \pm 83	161 \pm 155	-18 \pm 24
Jump Work neg (J)	240 \pm 256	204 \pm 249	236 \pm 294	196 \pm 230	214 \pm 267	164 \pm 216	-10 \pm 3
Jump Work pos (J)	334 \pm 363	309 \pm 347	316 \pm 348	355 \pm 348	319 \pm 350	325 \pm 371	-2 \pm 3
Jump Work abs (J)	574 \pm 621	513 \pm 596	552 \pm 641	551 \pm 578	532 \pm 618	489 \pm 587	-6 \pm 2
Jump Peak power neg (J)	1859 \pm 2897	2363 \pm 3120	2410 \pm 3157	2793 \pm 2971	2110 \pm 2621	2478 \pm 3170	11 \pm 7
Jump Peak Power pos (J)	1519 \pm 2089	1736 \pm 2110	1926 \pm 2075	1879 \pm 2091	1688 \pm 1962	1831 \pm 2100	-1 \pm 4

Evaluation by intervention (intervention x time)

Scrutiny of percentage change data histograms did not reveal gross deviation from normality and there was not a significant difference between the mean and median data (Shapiro-Wilk $p<0.05$). ANOVA (3x3) revealed no significant effect for intervention or time-intervention interaction in any DJ variables: Jump Height, Jump Flight Time, Jump Contact Time, Reactive Index, Jump Work_{net}, Jump Work_{neg}, Jump Work_{pos}, Jump Work_{abs}, Jump Peak Power_{neg} and Jump Peak Power_{pos}. There was a significant main effect of time for Jump Height, Jump Flight Time, Jump Contact Time, Reactive Index, Jump Work_{neg}, Jump Work_{pos}, Jump Work_{abs}, and Peak Power_{pos}. There was not a significant main effect of time for Jump Work_{net} and Jump Peak Power_{neg} ($p>0.05$). DJ variables following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest are contained in Table 6.5.

The illustrated percentage change from Pre-Ex in Jump Height, Figure 6.10, and Reactive Index (ratio of Jump Contact Time to Jump Flight Time), Figure 6.11, present a graphical overview of jump performance in trials of 5 minute interventions of cold water immersion, warm water immersion and rest. However, with established significant difference between Pre- and Post-Exercise and a reasonable SEM, variables Jump Work_{neg}, Jump Work_{abs}, and Jump Peak Power_{neg} were considered the strongest variables upon which to evaluate recovery. The percentage change of these variables over time is illustrated following recovery interventions

of 5 minutes of cold water immersion, warm water immersion and rest; Jump Work_{neg}, Figure 6.12; Jump Work_{abs}, Figure 6.13 and Jump Peak Power_{neg}, Figure 6.14.

Table 6.5 Drop Jump variables following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest

The mean \pm SEM of Drop Jump variables at 2 hours, 4 hours and 24 hours post-exercise following cold water immersion, warm water immersion and rest recovery interventions.

	2 hours			4 hours			24 hours		
	Cold	Warm	Rest	Cold	Warm	Rest	Cold	Warm	Rest
Jump Height (m)	0.43 \pm 0.02	0.44 \pm 0.02	0.43 \pm 0.02	0.46 \pm 0.02	0.44 \pm 1.97	0.44 \pm 0.02	0.42 \pm 0.02	0.43 \pm 0.02	0.42 \pm 0.02
Jump Flight Time (s)	0.59 \pm 0.01	0.60 \pm 0.01	0.59 \pm 0.01	0.61 \pm 0.01	0.60 \pm 0.01	0.60 \pm 0.02	0.58 \pm 0.02	0.59 \pm 0.02	0.58 \pm 0.02
Jump Contact Time (s)	0.50 \pm 0.05	0.50 \pm 0.05	0.49 \pm 0.05	0.49 \pm 0.05	0.51 \pm 0.06	0.51 \pm 0.05	0.50 \pm 0.06	0.52 \pm 0.06	0.53 \pm 0.05
Reactive Index	1.4 \pm 0.2	1.4 \pm 0.2	1.4 \pm 0.2	1.5 \pm 0.2	1.5 \pm 0.3	1.4 \pm 0.2	1.4 \pm 0.2	1.4 \pm 0.2	1.3 \pm 0.2
Jump Work net (J)	37 \pm 116	114 \pm 95	62 \pm 69	113 \pm 129	141 \pm 95	120 \pm 97	67 \pm 72	113 \pm 76	115 \pm 82
Jump Work neg (J)	219 \pm 245	217 \pm 267	249 \pm 267	228 \pm 257	211 \pm 259	209 \pm 259	239 \pm 267	211 \pm 266	201 \pm 250
Jump Work pos (J)	256 \pm 361	330 \pm 361	310 \pm 335	341 \pm 385	352 \pm 354	329 \pm 356	306 \pm 340	324 \pm 342	316 \pm 332
Jump Work abs (J)	475 \pm 606	547 \pm 628	559 \pm 602	568 \pm 642	563 \pm 613	538 \pm 615	545 \pm 607	534 \pm 608	517 \pm 582
Jump Peak power neg (J)	2167 \pm 4174	2795 \pm 4621	2506 \pm 1828	3238 \pm 3314	2393 \pm 3919	3131 \pm 4552	2400 \pm 3906	3405 \pm 2845	2191 \pm 4704
Jump Peak Power pos (J)	1435 \pm 2154	1951 \pm 2540	1858 \pm 2065	1728 \pm 2210	1992 \pm 2292	1794 \pm 2314	1618 \pm 2153	1698 \pm 1977	1856 \pm 2097

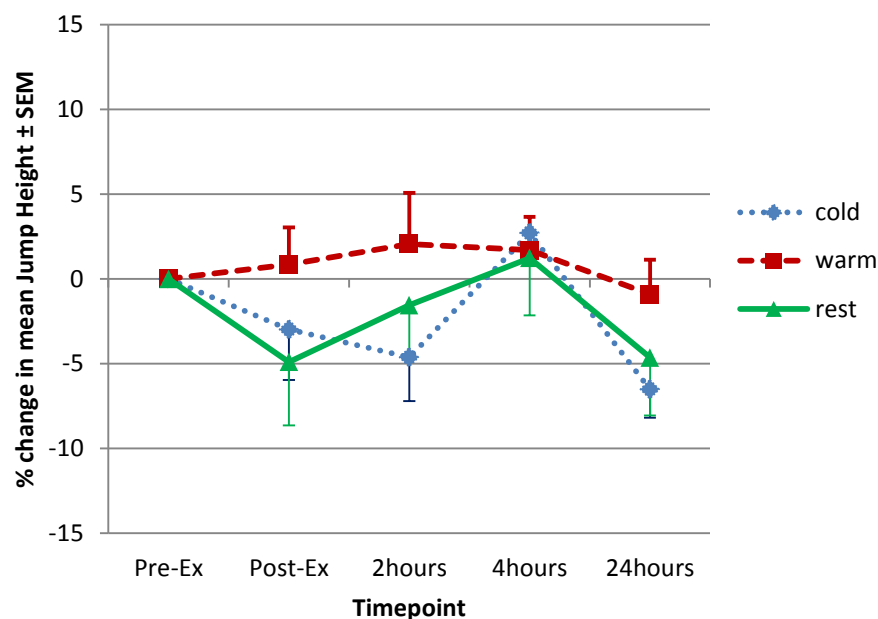


Figure 6.10 Jump Height percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM Jump Height for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

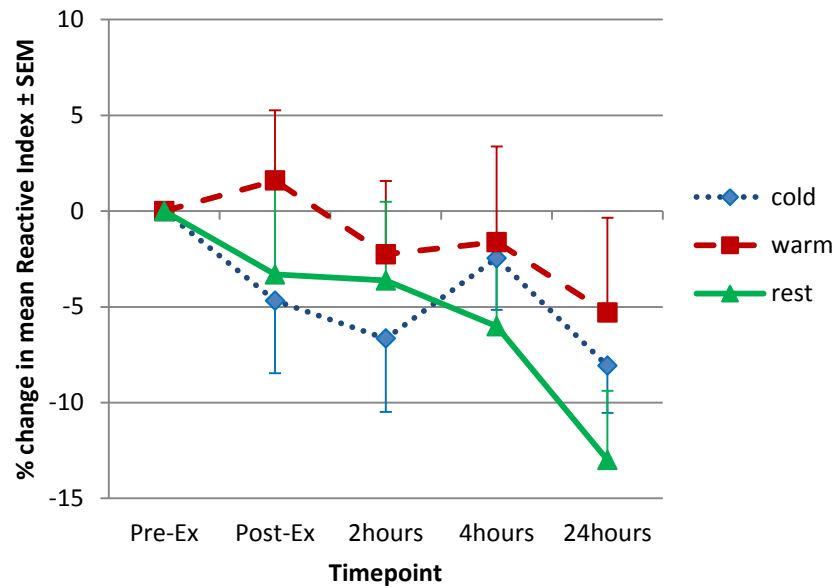


Figure 6.11 Reactive Index: percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM Reactive Index for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($--\blacksquare--$ dashed line; square markers) and rest ($-\blacktriangle-$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

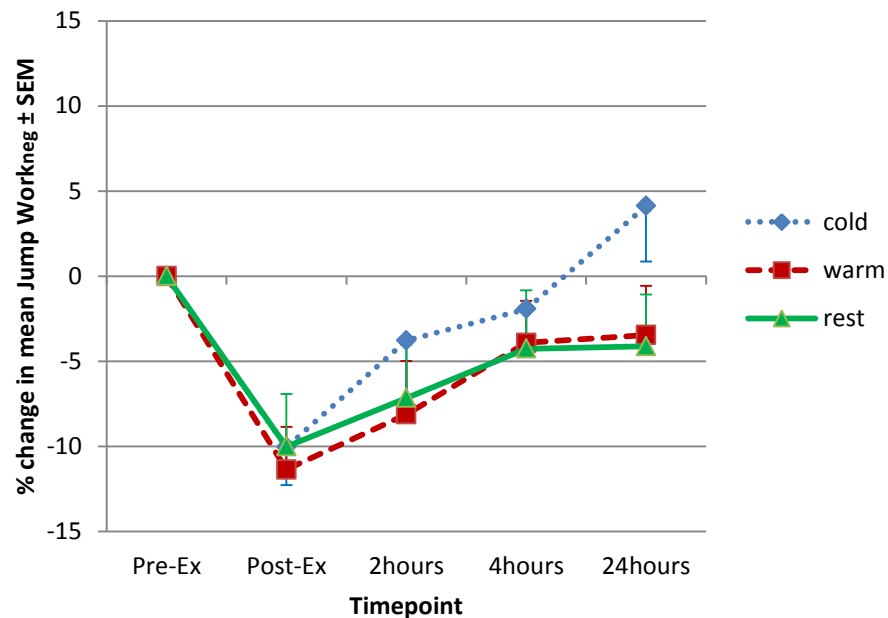


Figure 6.12 Jump Work_{neg} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM Jump Work_{neg} for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($--\blacksquare--$ dashed line; square markers) and rest ($-\blacktriangle-$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

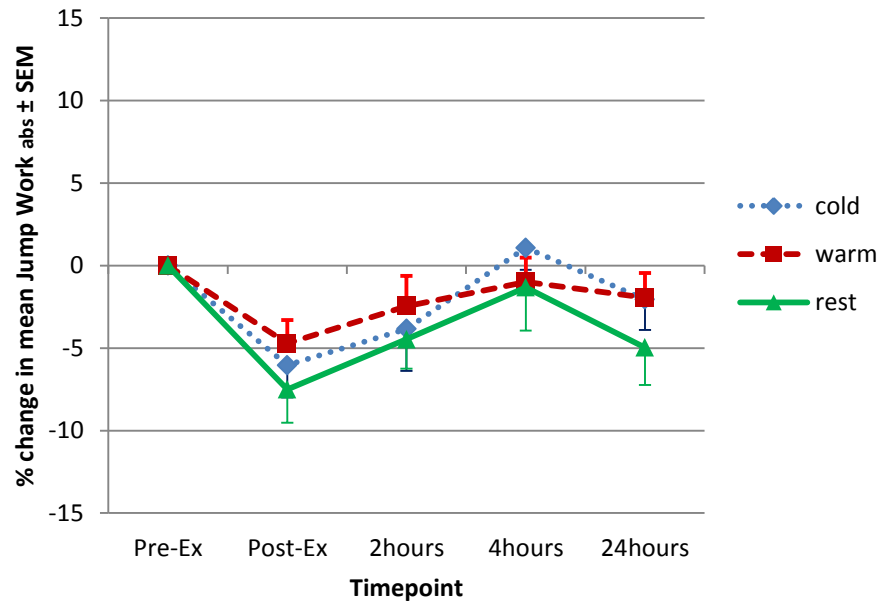


Figure 6.13 Jump Work_{abs} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM Jump Work_{abs} for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

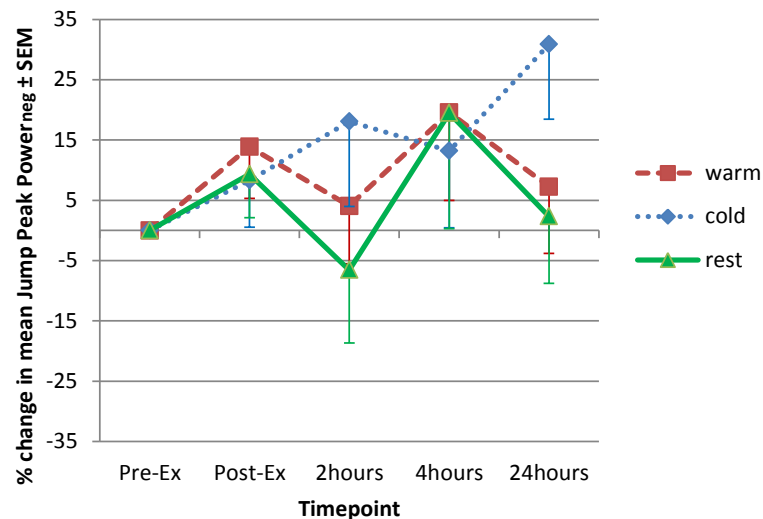


Figure 6.14 Jump Peak Power_{neg} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM Jump Peak Power_{neg} for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

6.3.3 Repeated Single Leg Hop (RH)

Evaluation of exercise (trial x time)

ANOVA (2x3) revealed no significant effect for trial or time-trial interaction in any variables. There was a significant main effect of time for the variable of Hop Work_{abs} ($p=0.01$) only. Change in Pre- and Post-Exercise RH variables are contained in Table 6.6.

Table 6.6 Repeated Single Leg Hop (RH) percentage change Pre- and Post-Exercise

For Trial 1, Trial 2 and Trial 3, the Pre-Exercise (Pre-Ex) and Post-Exercise (Post-Ex) mean \pm SEM of Repeated Hop variables* are shown along with the average percentage change across the three trials.

	Trial 1		Trial 2		Trial 3		Av % change
	Pre-Ex	Post-Ex	Pre-Ex	Post-Ex	Pre-Ex	Post-Ex	
Hop Height (tot) (m)	1.11 \pm 0.05	1.11 \pm 0.06	1.07 \pm 0.07	1.03 \pm 0.07	1.11 \pm 0.07	1.08 \pm 0.09	-2 \pm 3
Hop Height (av) (m)	0.19 \pm 0.01	0.19 \pm 0.01	0.18 \pm 0.01	0.17 \pm 0.01	0.18 \pm 0.01	0.18 \pm 0.01	-2 \pm 3
Hop Height (SD)	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	15 \pm 22
Hop Contact Time (tot) (s)	2.65 \pm 0.2	2.57 \pm 0.19	2.59 \pm 0.18	2.67 \pm 0.21	2.53 \pm 0.19	2.51 \pm 0.2	0.04 \pm 3
Hop Contact Time (av) (s)	0.53 \pm 0.04	0.51 \pm 0.04	0.52 \pm 0.04	0.53 \pm 0.04	0.51 \pm 0.04	0.5 \pm 0.04	0.04 \pm 3
Hop Contact Time (SD)	0.05 \pm 0.01	0.03 \pm 0	0.03 \pm 0	0.03 \pm 0	0.03 \pm 0.01	0.02 \pm 0	-9 \pm 13
Hop Flight Time (tot) (s)	2.32 \pm 0.05	2.32 \pm 0.06	2.26 \pm 0.07	2.22 \pm 0.08	2.31 \pm 0.08	2.27 \pm 0.09	-1 \pm 2
Hop Flight Time (av) (s)	0.39 \pm 0.01	0.39 \pm 0.01	0.38 \pm 0.01	0.37 \pm 0.01	0.39 \pm 0.01	0.38 \pm 0.02	-1 \pm 2
Hop Flight Time (SD)	0.02 \pm 0.01	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	17 \pm 20
Hop Displacement (m)	0.82 \pm 0.05	0.78 \pm 0.07	0.66 \pm 0.05	0.68 \pm 0.06	0.71 \pm 0.05	0.67 \pm 0.07	-1 \pm 7
Hop Work (abs) (J)	1956 \pm 190	1854 \pm 170	1828 \pm 188	1681 \pm 141	1697 \pm 180	1516 \pm 135	-6 \pm 2

* Note: For each variable Total and Average percentage change data are the same, due to the mathematical relationship

Evaluation of intervention (intervention x time)

RH variables following recovery interventions of 5 minutes cold water immersion, warm water immersion and rest are contained in Table 6.7.

Table 6.7 Repeated Single Leg Hop (RH) variables following recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest

The mean \pm SEM of Repeated Hop variables at 2 hours, 4 hours and 24 hours post-exercise following cold water immersion, warm water immersion and rest recovery interventions.

	2 hours			4 hours			24 hours		
	Cold	Warm	Rest	Cold	Warm	Rest	Cold	Warm	Rest
Hop Height (tot) (m)	1.1 \pm 0.06	1.04 \pm 0.07	1.04 \pm 0.08	1.07 \pm 0.06	1.09 \pm 0.07	1.09 \pm 0.08	1.04 \pm 0.07	1.02 \pm 0.08	1.04 \pm 0.08
Hop Height (av) (m)	0.18 \pm 0.01	0.17 \pm 0.01	0.17 \pm 0.01	0.18 \pm 0.01	0.18 \pm 0.01	0.18 \pm 0.01	0.17 \pm 0.01	0.17 \pm 0.01	0.17 \pm 0.01
Hop Height (SD)	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.01 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0
Hop Contact Time (tot) (s)	2.63 \pm 0.21	2.71 \pm 0.21	2.55 \pm 0.19	2.67 \pm 0.18	2.66 \pm 0.23	2.57 \pm 0.19	2.68 \pm 0.2	2.6 \pm 0.21	2.54 \pm 0.18
Hop Contact Time (av) (s)	0.53 \pm 0.04	0.54 \pm 0.04	0.51 \pm 0.04	0.53 \pm 0.04	0.53 \pm 0.05	0.51 \pm 0.04	0.54 \pm 0.04	0.52 \pm 0.04	0.51 \pm 0.04
Hop Contact Time (SD)	0.03 \pm 0	0.03 \pm 0	0.03 \pm 0	0.03 \pm 0.01	0.03 \pm 0.01	0.03 \pm 0	0.03 \pm 0	0.03 \pm 0	0.03 \pm 0
Hop Flight Time (tot) (s)	2.30 \pm 0.06	2.25 \pm 0.07	2.23 \pm 0.08	2.28 \pm 0.06	2.29 \pm 0.08	2.30 \pm 0.08	2.24 \pm 0.07	2.22 \pm 0.08	2.23 \pm 0.09
Hop Flight Time (av) (s)	0.38 \pm 0.01	0.37 \pm 0.01	0.37 \pm 0.01	0.38 \pm 0.01	0.38 \pm 0.01	0.38 \pm 0.01	0.37 \pm 0.01	0.37 \pm 0.01	0.37 \pm 0.01
Hop Flight Time (SD)	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0	0.02 \pm 0
Hop Displacement (m)	0.72 \pm 0.09	0.74 \pm 0.06	0.7 \pm 0.06	0.71 \pm 0.07	0.76 \pm 0.05	0.65 \pm 0.05	0.71 \pm 0.04	0.72 \pm 0.09	0.64 \pm 0.07
Hop Work (abs) (J)	1893 \pm 175	1782 \pm 166	1549 \pm 140	1885 \pm 193	1812 \pm 163	1633 \pm 146	1845 \pm 195	1750 \pm 178	1582 \pm 154

Due to the mathematical relationship, Total and Average percentage change data were the same for Hop Height, Hop Contact Time and Hop Flight Time. As such data describing the Total were analysed and presented where relevant. Scrutiny of percentage change data histograms did not reveal gross deviation from normality and there was no significant difference between the mean and median data (Shapiro-Wilk $p>0.05$) for Hop Contact Time_{tot&av}, Displacement and Hop Work_{abs} variables. The distribution of data for all other variables showed significant deviation from normality (Shapiro-Wilk $p\leq 0.05$). With no violation of the normality assumption and established significant difference between Pre- and Post-exercise the variable Hop Work_{abs} was considered the strongest variable upon which to evaluate recovery. Figure 6.15 illustrates the Hop Work_{abs} percentage change from Pre-Exercise in trials of recovery interventions of 5 minutes of cold water immersion, warm water immersion and rest.

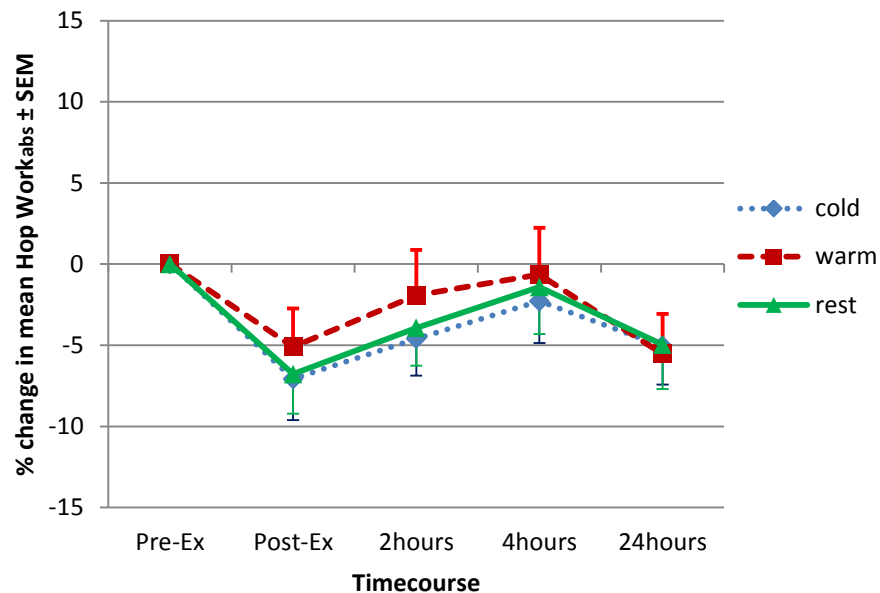


Figure 6.15 Hop Work_{abs} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean \pm SEM Hop Work_{abs} for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- - \blacksquare - -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

ANOVA (3x3) revealed no significant effect for intervention or time-intervention interaction in any RH variable: Hop Work_{abs}, Hop Height_{tot}, Hop Height_{SD}, Hop Contact Time_{tot}, Hop Contact Time_{SD}, Hop Flight Time_{tot}, Hop Flight Time_{SD} and Displacement. There was a significant main effect of time in Hop Height_{tot} ($p=0.01$) and Hop Flight Time_{tot} ($p=0.01$). The percentage change from Pre-Exercise in Hop Height_{tot}, Figure 6.16 and Hop Flight Time_{tot}, Figure 6.17 is illustrated in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions.

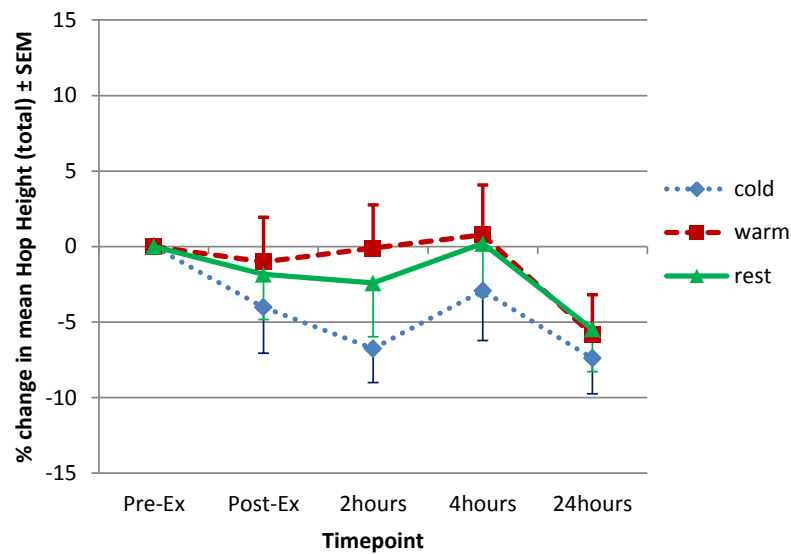


Figure 6.16 Hop Height_{tot} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in mean ± SEM Hop Height_{tot} for trials involving cold water immersion (···◆·· dotted line; diamond markers), warm water immersion (- - ■ - - dashed line; square markers) and rest (-▲- unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

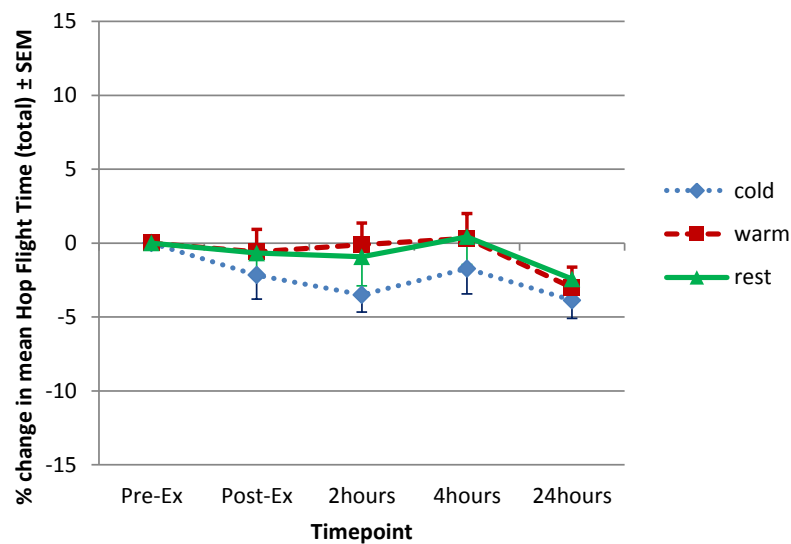


Figure 6.17 Hop Flight Time_{tot} percentage change from Pre-Exercise in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

The percentage change from Pre-Exercise (Pre-Ex) in Hop Flight Time_{tot} for trials involving cold water immersion (···◆·· dotted line; diamond markers), warm water immersion (- - ■ - - dashed line; square markers) and rest (-▲- unbroken line; triangle markers), at time-points Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

6.3.4 Exploratory analysis

6.3.4.1 Correlation of Jump Height performance and selected potentially contributing variables

No single protocol can explain all the variance associated with performance and tests providing a global sense of function and also discriminate between components have been proposed as most useful (Maulder & Cronin, 2005). Furthermore the same maximal voluntary contraction can be produced using different patterns of muscle recruitment (Chapter 3), demonstrating that a given performance output could be achieved and maintained with different underlying mechanisms. This could have implications for efficiency, injury and consistency. No significant post-exercise change was observed in the performance indicator Jump Height, whilst significant post-exercise detriment was observed in KE Peak Torque, KF Peak Torque, Jump Work_{abs}, Jump Work_{neg} and Jump Peak Power_{neg}, which conceivably contribute to jump performance. Similarly, no significant post-exercise change was observed in the performance indicator Hop Height, whilst significant post-exercise detriment was observed in Hop Work_{abs}. To explore the relevance of these subsidiary components to athletic performance, the correlation between the performance indicator of Jump Height and potential subsidiary contributing variables were considered. The statistical correlations in order of strength are contained in Table 6.8.

Table 6.8 Correlation of the performance indicator Jump Height with potentially contributing variables

Correlation of the performance indicator Jump Height with potentially contributing variables, ranked in order of correlation strength.

Correlation with Jump height			
Rank strength	Variable	Pearson's r	significance p value
1	Jump Flight Time	1.00	<0.001
2	Jump Work pos	0.93	<0.001
3	Jump Work abs	0.86	<0.001
4	KE peak torque	0.70	<0.001
5	Reactive Index	0.53	0.001
6	Jump Work neg	0.51	0.001
7	KF peak torque	0.51	0.001
8	Jump Peak Power neg	0.27	0.066
9	Jump Contact Time	0.10	0.202

Jump Flight Time ($r=1.00$, $p<0.01$) showed the strongest correlation with Jump Height, which was expected given the mathematical relationship. There were also very strong correlations with Jump Work_{pos} ($r=.93$, $p<0.01$) and Jump Work_{abs} ($r=0.86$, $p<0.01$) and reasonable correlation with KE Peak Torque ($r=.70$, $p<0.01$). Jump Contact Time did not correlate with Jump Height ($r=.10$, $p>.05$).

This correlation analysis validated the relevance to performance analysis of variables KE Peak Torque, KF Peak Torque and Jump Work_{abs}, which had significant post-exercise change and significant correlation with Jump Height. They are therefore arguably of clinical interest. Figure 6.18 illustrates the correlation of Jump Height with KE Peak Torque, KF Peak Torque and Jump Work_{abs}.

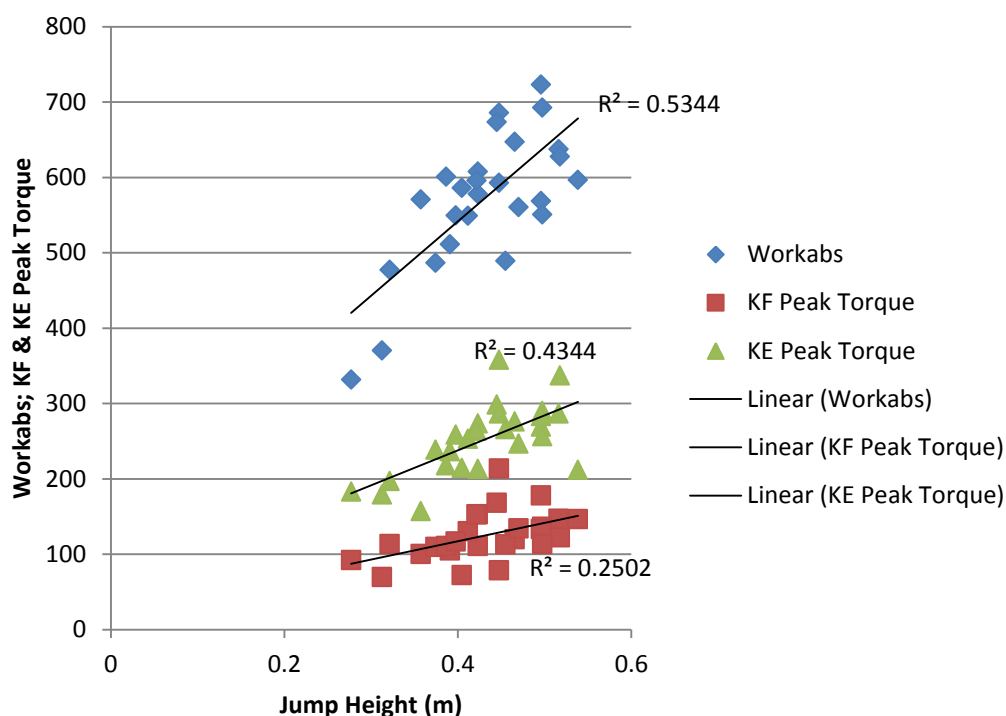


Figure 6.18 Correlation of Jump Height with Functional Performance Indicators: Jump Work_{abs} (J), KF Peak Torque (N.m) & KE Peak Torque (N.m)

The correlation of Jump Height (horizontal axis) with KE Peak Torque (\blacktriangle ; triangle markers), KF Peak Torque (\blacksquare ; square markers) and Jump Work_{abs} (\blacklozenge ; diamond markers). These variables had significant post-exercise change, significant correlation with Jump Height and are also arguably of clinical interest.

6.3.4.2 Exploratory evaluation of the recovery time-course in functional performance indicators

A pattern of significant post-exercise decrement, recovery trajectory towards Pre-Exercise levels at 2 hours and 4 hours, and emerging detriment at 24 hours was observable in the time-course of several variables describing neuromuscular function. This was most evident in variables also considered to be of clinical interest: KE Peak Torque, Jump Height, Jump Work_{abs}, Hop Work_{abs} and Hop Height. At 4 hours the mean post-exercise decrement had returned to within 5% variation from Pre-Exercise performance, followed by a larger mean decrement at 24 hours. This raised the possibilities of a delayed effect of exercise on these variables; or that this study did not capture the complete neuromuscular function recovery time-course.

This trajectory of return to Pre-Exercise levels without intervention was further explored in these variables, which were particularly relevant as they had significant Post Exercise change

and correlation with height performance. (With the exception of Jump Height and Hop Height but which provided the most direct performance indicators.) Figure 6.19 illustrates the post-exercise time-course of KE Peak Torque, KF peak torque, Jump Work_{abs} and Hop Work_{abs} without intervention; in the control trial of rest. This is contextualised alongside illustration of the time-course of performance indicators Jump Height and Hop Height.

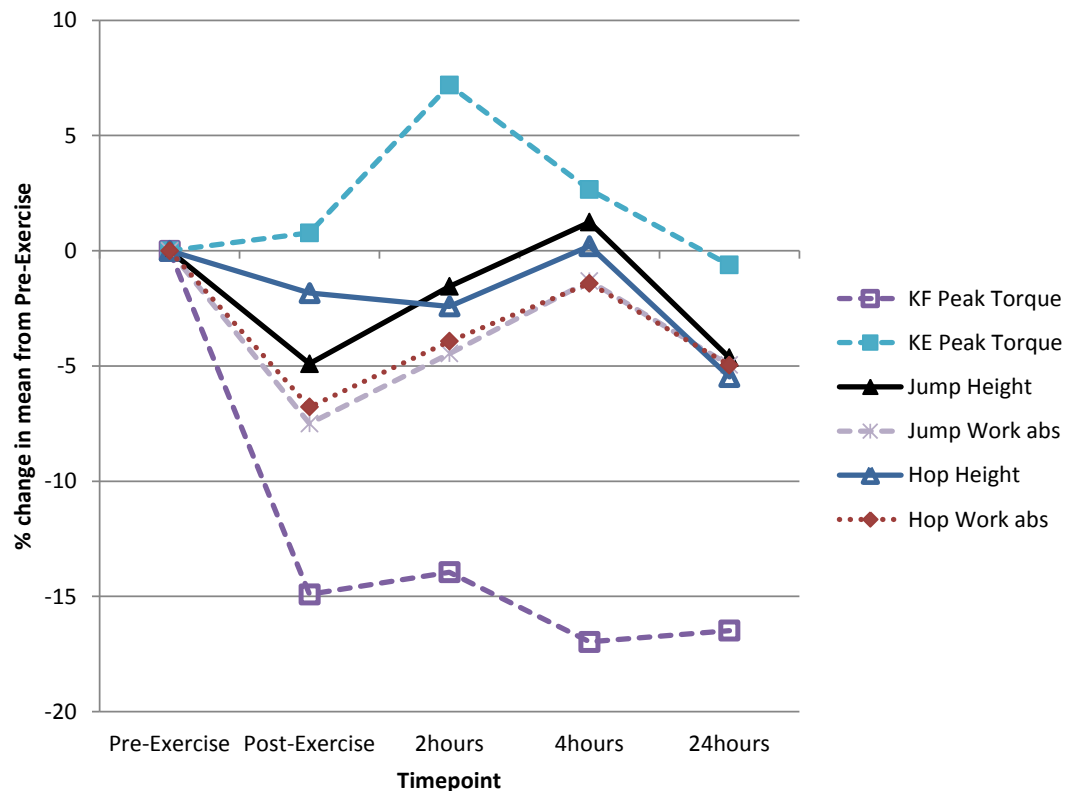


Figure 6.19 The percentage change in mean from Pre-Exercise in performance indicators Jump Height and Hop Height and selected clinically relevant variables with a significant Post Exercise change in the control trial of rest. The percentage change in mean KE Peak Torque (---■---; solid square markers, dashed line), KF peak torque (---□---; square markers no fill, dashed line), Jump Work_{abs} (---*---; asterisk markers, dashed line), and Hop Work_{abs} (···◆···; diamond markers, dotted line) in the control trial of rest. This is contextualised alongside the time-course of performance indicators Jump Height (—▲—; triangle markers, solid line), and Hop Height (—△—; triangle markers no fill).

For variables with significant post-exercise change and no effect of intervention, pre-planned paired t-tests compared KF Peak Torque, Jump Work_{abs}, and Hop Work_{abs} Pre-Exercise levels with 2 hours, 4 hours and 24 hours following the control condition of rest. At 2 hours, 4 hours and 24 hours there was a significant difference to Pre-Exercise in KF Peak Torque ($p \leq .01$). The difference between Pre-Exercise and 2 hours, 4 hours and 24 hours was not significant for Jump Work_{abs} and Hop Work_{abs} ($p > .05$). Application of the Ryan-Holm-Bonferroni correction for multiple comparisons is presented in Table 6.9.

Table 6.9 Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons of Pre-Exercise (Pre-Ex) with 2 hours, 4 hours and 24 hour levels of time for KF Peak Torque, Jump Work_{abs}, and Hop Work_{abs} in the control condition of rest

Pre-planned post-hoc paired t-tests compared KF Peak Torque, Jump Work_{abs} and Hop Work_{abs} Pre-Exercise (Pre-Ex) with 2 hours, 4 hours and 24 hours levels of time following the control condition of rest. The corrected p value (P_{BON}) is given by $m \times p$; where p is the uncorrected p value and m is the total number of comparisons made amongst factor levels (Atkinson, 2002).

Presentation of the Ryan-Holm-Bonferroni procedure for multiple comparisons: comparison to Pre-Ex following the control condition "rest"				
variable	comparison of level means	uncorrected p value	value of m in Bonferroni correction	corrected p value (P_{BON})
KF Peak Torque	Pre-Ex vs 2 hours	<0.001	3	<0.001
	Pre-Ex vs 4 hours	<0.001	2	<0.001
	Pre-Ex vs 24 hours	0.01	1	0.01
Jump Work _{abs}	Pre-Ex vs 2 hours	0.03	3	0.09
	Pre-Ex vs 24 hours	0.05	2	0.11
	Pre-Ex vs 4 hours	0.63	1	0.63
Hop Work _{abs}	Pre-Ex vs 24 hours	0.10	3	0.30
	Pre-Ex vs 2 hours	0.12	2	0.30*
	Pre-Ex vs 4 hours	0.64	1	0.64

* p value found to be smaller than the preceding p value and adjusted to equal the preceding p value

6.4 Discussion

There was no trial order effect for any variables and significant post-exercise decrements were observed in several variables, demonstrating the LIST as a suitable fatigue platform upon which to evaluate the effect of water immersion on neuromuscular function recovery.

Isometric peak torque

Significant decrements in KF Peak Torque and KE Peak Torque were demonstrated following the LIST. Morton et al., (2005) showed low systemic MVC variation within and between days in healthy well-familiarised males, concluding that variation above 5% could be attributed to muscle damage. The LIST induced average decrements of 12% in KF Peak Torque and 6% in KE Peak Torque substantiating the likelihood that muscle damage was induced in these muscle groups.

KF Peak Torque impairment persisted at 24 hours and there was no effect of intervention. There was a significant effect of intervention on KE Peak Torque ($p=.01$). Statistically significant lower KE Peak Torque followed water immersion compared with rest, and lower KE Peak Torque followed cold water immersion compared with warm water immersion. This suggests that water immersion, particularly cold water immersion, was detrimental to the recovery of KE Peak Torque.

However, it is possible that there was larger natural variability in KE Peak Torque which should be acknowledged when drawing conclusions about efficacy. Although there was an average Post-Exercise decrement of 6% across trials, KE Peak Torque was observed to decline or improve post-exercise. (This is evident in Figure 6.9 and Figure 6.19, where the average Post-Ex KE Peak Torque was greater than Pre-Ex in trials involving Rest.) This inconsistent post exercise response was not observed in KF Peak Torque. These peak torque patterns were expected, and consistent with previous muscle dynamometry following the LIST exercise protocol (Betts et al., 2009; Thompson et al., 1999). KE Peak Torque therefore did not provide a compelling measure upon which to judge water immersion intervention efficacy in isolation, supporting the consideration of a spectrum of outcome measures to inform practice decisions. Consistent findings following consistent exercise and immersion protocols are required to substantiate this effect.

Despite a reluctance to draw conclusions based solely on KE Peak Torque, there is other evidence suggesting cold water immersion is detrimental to muscle strength recovery. Peiffer et al., (2008) showed 12% fatigue-decrement in knee extension MVC (at 60°) with superimposed electrical stimulation, with a 13% decrement remaining up to 90 minutes post cycling time trial and 20 minutes of cold water immersion, compared with passive recovery. The apparently larger effect on knee extension could be attributed to different post exercise responses following their cycling time trial in the heat, versus shuttle running in this study. Nevertheless, given that there was no difference between voluntary and electrically superimposed contraction force, both post-exercise and recovery effects were reported as likely due to peripheral contractile capacity rather than central inhibition.

It is unlikely that water immersion recovery interventions have different effects on different muscle groups, and differences in natural variation, measurement reliability and fatigue pattern provide a possible explanation. With the statistical effects acknowledged, the balance of probability when making decisions regarding water immersion recovery efficacy should favour results obtained from the most reliable outcome measures, in this case KF Peak Torque.

Drop Jump

Maximal jump height, potential for 'air time' and quick ground reaction are desirable performance characteristics of many games sports. Therefore the Drop Jump characteristics most representative of skill performance were Jump Height, Jump Flight Time and Jump Contact Time. Force plate data provided a direct and highly accurate measurement of these variables and ought to have provided meaningful results. However, the percentage change across all time-points was extremely small (Table 6.4, Table 6.5) and there was no detectable Post-Exercise decrement or effect of water immersion intervention over the recovery time-course. It is possible to conclude that jump performance is not affected by fatigue or water immersion, although it is also possible that athletes were able to compensate for fatigue related changes by altering their technique.

Technique changes may counterbalance the effect of fatigue on performance (Byrne & Eston, 2002), maintaining a similar output function through increased muscle fibre recruitment

(Noakes et al., 2005). This could explain the absence of post-exercise decrements or change over time in gross Drop Jump and Repeated Hop performance variables, and would be consistent with a pilot study showing that the same functional outcome could be achieved using a variety of muscle fibre type recruitment patterns (Chapter 3). Evaluation of jump components was therefore pertinent and better able to identify where variation was located.

With significant Post-Exercise decrement, variables Jump Work_{neg} and Jump Work_{abs} were considered the strongest variables upon which to evaluate recovery. Decrement in Jump Work_{neg}, and not in Jump Work_{pos}, indicated functional decrement in the capacity to generate work occurred specifically during the landing phase. This decrease in the capacity to control the GRF vector acting on the CoM was expected post-exercise, which could manifest as a decrease in movement efficiency or greater effort to control the CoM and achieve the same Jump Height.

Specifically, statistically significant post-exercise differences were observed in variables describing negative work; or work done during the landing phase of the jump. Therefore these results did not support the specific hypothesis that a decrease in negative work during the eccentric phase would result in a decreased capacity for positive work during the concentric phase, utilising the GRF to generate the jump height. It seems that significant changes observed in the landing phase could be compensated for, resulting in an undetectable change in Jump Height. As a function of Jump Work_{neg} and Jump Work_{pos}, the less marked effect observed in Jump Work_{abs} could be attributable to the absence of effect in the Jump Work_{pos} subsidiary.

Statistically, there was no effect of cold or warm water immersion on variables describing Drop Jump, and the recovery trajectory suggested recovery to Pre-Exercise occurred between 2-4 hours regardless of intervention.

Repeated Single Leg Hop

Hop Height, Hop Contact Time and Displacement provided the most direct description of the ability to hop as high as possible, as quickly as possible and remaining on the same spot. The LIST induced minimal Post-Exercise decrements in these measures. Hop Work_{abs} was the only variable to have significant post-LIST decrement (and also did not violate the assumption of normality), therefore the results can be interpreted with reasonable reliability. There was no effect of cold or warm water immersion compared to rest.

Fatigue-induced biomechanical changes to single leg hop landing technique have been demonstrated (Augustsson et al., 2006; Orishimo & Kremenic, 2006), and fatigue-induced deterioration from optimal athletic technique occurs in an unpredictable and non-linear pattern (Barden & Kell, 2009). Analysis of technique at multiple levels is therefore appropriate and necessary to capture a full picture of skill performance, and the approach within this study may not have included analysis of components necessary to illuminate effects of water immersion.

Exploratory discussion: informing future research

There was no main intervention effect on variables describing Drop Jump and Repeated Hop, however proposing the relevance of variables to athletic skill performance and describing the recovery timeline in the absence of intervention was relevant to informing future research.

A noteworthy pattern of significant post-exercise decrement, seeming recovery trajectory towards Pre-Exercise levels at 2 hours and 4 hours, and emerging detriment at 24 hours was observable in variables describing neuromuscular function. This raised the possibilities of a delayed effect of exercise on these variables; or that this study did not capture the complete neuromuscular function recovery time-course which further research could more clearly delineate.

The clinical implications of this pattern should not be overstated, as the analytical intention was exploratory rather than rigorous. Furthermore several variables are mathematically related and therefore similar patterns might be expected. However, this apparent pattern was consistent between variables describing different functional tests of isometric MVC, Drop Jump and Repeated Hop. Pre-sample behaviour and warm-up at 2 hours, 4 hours and 24 hour time-points were standardised in this study (Refer 4.6 Experimental protocol) and therefore should not have influenced the results, but it is possible that circadian rhythm precipitated capacity to produce maximum neuromuscular function.

Functional performance skills are often divided into subsidiary variables with the pretence of enhancing analytical detail. To ensure this detailed analysis contributes rather than distracts from the intended purpose it is important that these variables are selective and relevant to performance outcomes. Achieving maximum vertical jump height is a highly desirable performance outcome, although the LIST did not induce a significant Jump Height decrement. Correlation analysis validated the relevance to performance analysis of variables KE Peak Torque, KF Peak Torque and Jump Work_{abs}, which had significant post-exercise change, significant correlation with Jump Height and are also arguably of clinical interest.

KE Peak Torque correlated with Jump Height, demonstrating it to be a useful measure of performance potential. However, the inconsistent Post-Exercise decrement suggested either that muscle damage was inconsistently induced, or that induced damage did not always impair peak torque production. Jump and hop movement patterns place high demand on the knee extension muscle group and jump performance decrements therefore may have been less likely in this situation where the extensor force producing capacity was less impaired. The LIST provided a running based exercise protocol, movement patterns which induced significant and consistent functional decrement in KF Peak Torque. However KF Peak Torque capacity may have been less consequential to jump performance.

Variables describing the drop jump concentric (take-off) phase, Jump Work_{abs} and Jump Work_{pos} correlated most strongly with Jump Height. This was fitting because the ability to utilise the GRF during the propulsive phase should extrapolate to the generation of maximum take-off velocity. However, the eccentric phase was where most post-exercise decrements were observed which was consistent with kinematic changes observed in hop landing in other studies (Augustsson et al., 2006; Orishimo & Kremenec, 2006). Although the stretch-shortening

cycle can compensate for muscle strength loss (Byrne & Eston, 2002) and it is not unreasonable to accept this compensation when evaluating a functional outcome, focus on this jump phase in future research would concur with the growing body of evidence associating eccentric landing with injury (Wilkstrom et al., 2008).

Although quick Contact Time was a key instruction in Drop Jump performance, longer contact times allow force generation over a longer period of time, and could therefore be advantageous in achieving maximum jump height. Based on a similar mathematical principle, Dowling & Vamos (1993) concluded that peak power is a necessary component of achieving peak vertical height, although the highest power did not always result in the highest jump. Calculation of power in this study enabled scrutiny of the capacity to generate force quickly which is crucial to take off velocity but variables other than power had a stronger relationship to jump performance. Further research could consider the relative advantages of maximum force generation versus short contact times.

It is reasonable to conclude that improved neuromuscular function and improved performance of simple athletic skills are desirable in maximising the performance of complex sport skill sequences, and identifying relevant subsidiary components is important for proposing mechanisms of action and targeting interventions.

Implications for water immersion recovery practice

Water immersion influenced the recovery of one variable relating to neuromuscular function: there was an apparent detrimental effect of water immersion compared to rest and cold water compared to warm water immersion on KE Peak Torque. This detrimental influence was not observable on overall skills of Drop Jump and Repeated Hop, or across the spectrum of variables representing neuromuscular function.

The different post-exercise response and recovery time-courses observed could indicate that MVC, Drop Jump and Repeated Hop performance have different principal neural and systemic determinants, and that water immersion and the temperature effects these systems differently over time. It is possible that underlying neural mechanisms are acute, while systemic mechanisms manifest over a more prolonged time period. Particularly, the recovery time-course and effects of water immersion on neuromuscular function in the 2-4 hours post exercise warrants clarification, as this time period could be crucial to athletes engaging in subsequent exercise bouts on the same day.

Limitations of study design & areas for further research

Cormie et al., (2009) caution that observed improvements could be attributed to improved technique versus physiological changes. No trial order effect was observed in this study, advocating the subject familiarisation process avoided bias due to technique improvements over time. However, variables in this study were indicators, not descriptors, of the underlying physiological mechanisms responsible for change in neuromuscular function.

Low average percentage change but high variability (indicated by SEM) was generally observed in force plate variables. These variables may not have been sensitive enough to detect small changes or demonstrate a significant difference in this subject population. Statistically, multiple comparisons must be acknowledged, which increased the likelihood of determining a significant effect by chance. While multiple comparisons were selectively conducted and statistically corrected, this could have compromised identification of clinically important small effects. Further studies with larger subject numbers could assist identification of small effects or substantiate non-significant observations.

The strength of conclusions drawn is defined by the identification and selection of outcome measures that are both reliable and functional. The data scrutiny process sought to determine sufficiently reliable and valid variables to evaluate post-exercise changes in muscle function and upon which to evaluate recovery intervention efficacy. Further reliability studies are necessary to identify appropriate outcome measures which would enable cause and effect to be concluded with confidence.

The direction of landing is important in the analysis and evaluation of landing technique and association with injury (Clark et al., 2002; Wikstrom et al., 2008). The Drop Jump and Repeated Hop were predominantly demanding in the single vertical plane. This removed confluence of the results with variation in the lateral and horizontal dimensions but limited inferences of multi-directional movement which are key components of athletic performance. Further research could improve the relevance of laboratory testing to athletic performance through selecting an alternative spectrum of outcome measures.

Consistent with the literature, force plate data showed evidence that technique adaptations can compensate for fatigue-related changes in muscle function. There was no effect of water immersion on gross measures of Drop Jump and Repeated Hop performance, and further research is needed to establish the effects of fatigue on technique. Although technique was represented using indices derived mathematically and systematically, direct measures of muscle recruitment patterns and kinematic measures would have enabled improved scrutiny.

Ross, Guskiewicz, Prentice, Schneider & Yu (2004) observed difference in landing technique between dominant and non-dominant legs. Similarly, landing and force generation limb differences were evident in force plate data in this study, however analysis of unilateral variables was not undertaken. Limb differences in jump and landing technique could be highly relevant to the transfer of force through the kinematic chain and worthy of further research. Force traces also showed variability in landing technique and oscillation in controlling the centre of mass deceleration and acceleration which could be relevant and therefore useful to quantify.

Muscle activation preparatory to landing has been associated with injury prevention strategies (Wilkstrom et al., 2008). A pilot study showed that the EMG-wavelet analysis approach to measuring muscle activation patterning was not sufficiently reliable for application in this study (Chapter 3). However, a more reliable EMG technique could measure both preparatory activation and the neuromuscular patterning throughout the jump.

Voluntary effort is often suboptimal, which can lead to inaccurate conclusions regarding muscle force capacity (Gandevia, 2001). This study could not be certain that performance was a “true maximum” or isolate peripheral and central determinants of fatigue and recovery. Wikstrom et al., (2008) suggested that athlete perception of the difficulty of the task could influence performance, though reserve judgement on whether a challenging test presents a positive or negative motivator. In addition to the familiarisation process, the Drop Jump test was highly familiar to the trained athlete population, however the perceived difficulty of the less familiar Repeated Hop test could have influenced the results.

6.5 Chapter summary

While water immersion, particularly cold, was observed to impair the recovery of KE Peak Torque, water immersion did not affect the recovery of other neuromuscular function variables. There was no effect of cold or warm water immersion on variables describing Drop Jump or Repeated Hop. There was no effect of water immersion on KF Peak Torque and it is unlikely that water immersion recovery interventions influences different muscle groups differently. The post-shuttle running response and recovery of KE Peak Torque was more variable and differences in natural variation, measurement reliability and fatigue pattern could have contributed to this finding. Consistent findings following consistent exercise and immersion protocols are required to substantiate this effect.

There was an extremely small percentage change across all time-points in Jump Height, Jump Flight Time, Jump Contact Time, Hop Height, Hop Contact Time, Hop Flight Time and Displacement irrespective of intervention. It is possible to conclude that Drop Jump and Repeated Hop performance were not affected by this exercise protocol or water immersion, although changes in subsidiary components indicated a likelihood that altered technique could compensate for fatigue related changes. Significant Post-exercise decrements were observed in Jump Work_{neg}, Jump Work_{abs} and Hop Work_{abs}, indicating a pattern of functional decrement in the capacity to generate work specifically during the landing phases.

Exploratory analysis validated the relevance to performance analysis of variables KE Peak Torque, KF Peak Torque, Jump Work_{abs} and Hop Work_{abs}. These had significant post-exercise change and typically correlated with the most direct performance indicators of Jump Height and Hop Height. These variables were therefore considered most clinically relevant.

The different recovery time-courses observed could indicate that MVC, Drop Jump and Repeated Hop performance have different principle neural and systemic determinants, and that water immersion and temperature effects these systems differently over time. It is possible that underlying neural mechanisms are acute, while systemic mechanisms manifest over a more prolonged time period. It is also possible that these findings are a product of natural variation, measurement error or chance.

Chapter 7 THE EFFECT OF WATER IMMERSION ON PERCEIVED RECOVERY

7.1 Introduction

Athlete and support staff compliance is vital for effective interventions (Bishop, 2008) and athletes may engage specifically with recovery interventions they believe are most beneficial. Anecdotal evidence underpins the clinical application of recovery interventions (Wilcock et al., 2006) so evaluating the perception of treatment efficacy and preferred intervention is important alongside other measures of recovery and performance. It is also possible that the outcome measure profile of this study did not comprehensively illustrate potential physiological effects and mechanisms of water immersion recovery interventions. Finding an overwhelming athlete intervention preference would suggest further investigation is worthwhile.

Although 'perception' could construe a source of bias within a scientific paradigm, it is central to the definition of fatigue. Fatigue has been described as "a sensation that results from the conscious perception and interpretation of subconscious regulatory processes in the brain" where the brain 'paces' and limits physical exertion to maintain multi-system homeostasis (Noakes et al., 2005, p123). Recovery could therefore be defined as resolution of the sensation of fatigue to a pre-exercise state. This definition also infers that *how it feels matters*, which could be represented by perceived fatigue and perceived recovery.

Post-exercise muscle soreness may be produced by several morphological and biochemical factors and a 'tired, numb' sensation versus 'actual' soreness can be differentiated (Rodenburg et al., 1993). These sensations are further distinct from Delayed Onset Muscle Soreness (DOMS) which describe the typical muscle soreness most frequently experienced in response to unfamiliar eccentric exercise (Cheung et al., 2003). These descriptors of post exercise experiences are helpful but varied, and greatest muscle soreness can be expected 1-4 days post-exercise (Prasartwuth, Taylor & Gandevia, 2005). Thus, substantial muscle soreness to influence performance in this population of trained and familiarised athletes was not anticipated within the 24 hour timeline of this study. Therefore participants were asked to rate overarching perceived fatigue and perceived recovery on a visual analogue scale. Visual analogue scales (VAS) are recommended by the American College of Sports Medicine (ACSM) to measure exercise intensity (ACSM, 2008) and have been used as measures of perceived pain or muscle soreness in several previous studies evaluating recovery (Rowell et al., 2009; Vaile et al., 2008).

Desirable effects on perceptual measures have followed water immersion including perceived pain (Vaile et al., 2008), muscle soreness (Bailey et al., 2007) and relaxation (Suzuki et al., 2004). However Rowell et al., (2009) is the only other study to specifically evaluate perception of fatigue following cold water immersion, reporting less general fatigue following 10°C water immersion than 34°C water immersion using a 1-10 scale. Hornery et al., (2005) recorded favourable emotional ratings of cooling jacket application but attributed this to a placebo effect.

The placebo effect of clinical interventions is well described and there is growing speculation of its effect on sports performance (Beedie & Foad, 2009). The placebo effect historically refers to the *suggestion* of benefit associated with an intervention (Beecher, 1955), and expansion of the concept refers to any kind of benefit without an otherwise well explained scientific effect (Moerman & Jonas, 2002). Although the efficacy of water immersion in athlete recovery is genuinely unclear, subjects' expectations of undertaking an active intervention versus control condition could have produced a placebo effect of cold and / or warm water immersion in this study.

However, perceived recovery should be considered an element of recovery in its own right as deconstructing the placebo effect is complex and constituent 'real' effects rather than inert phenomena are likely (Moerman & Jonas, 2002). It is also plausible that perceived recovery could actually influence performance. Marcora & Bosio (2007) suggested that "sense" of effort influences endurance running performance and athletes perform better when they believe they have undertaken beneficial intervention (Beedie, 2007; Clark, Hopkins, Hawley & Burke, 2000).

Interventions that promote a feeling of wellbeing could similarly aid recovery. Water immersion can facilitate relaxation (Suzuki et al., 2004) and a 'wellbeing' sensation can follow decreased arousal levels and increased endorphins (Hemmings, Smith, Graydon & Dyson, 2000). Cold exposure can increase endorphins (Schoenfeld, Lox, Chen & Lutherer, 1985) while cryotherapy increases the pain threshold and pain tolerance at both the site of application and in the distribution of the nerve (Algaflly & George, 2007). Decreased pain is a conceivably favourable condition to athletic performance, independent to physiological muscle recovery, and Newham et al., (1987) observed the awareness of muscle function inhibition and muscle weakness only in the presence of muscle soreness. In contrast, voluntary muscle activation, force production, pain during contraction and muscle tenderness can have different post-exercise time-courses, suggesting that reduced force is not due to muscle soreness (Prasartwuth et al., 2005). Nevertheless, the interaction of psychological and physiological factors and the influence on sport performance are being increasingly explored (Beedie & Foad, 2009).

Although the several mechanisms are speculative, it was therefore hypothesised that increased perceived recovery and decreased perceived fatigue would follow both cold and warm water immersion and be preferable to passive rest regardless of demonstrable physiological effects.

7.2 Method

Perceptual measures of recovery were at Pre-Exercise, Post-Exercise, 2 hours, 4 hours and 24 hour time points. Pre-sample behaviour at each of these time-points was standardised and consistent, and the laboratory methods are described fully in Chapter 4, 4.6.1 Outcome measurement. The following variables were evaluated:

Perceived Fatigue (PF)

Perceived Recovery (PR)

Preferred Intervention

Least Preferred Intervention

7.3 Results

7.3.1 Evaluation of exercise (trial x time)

ANOVA (3x2) revealed a significant difference between Pre- and Post-exercise ($p < 0.05$) and no significant difference between trials ($p > 0.05$) for PF and PR.

Pre- and Post- Exercise means and mean % change in Perceived Fatigue (PF) and Perceived Recovery (PR) for Trials 1, 2 and 3

For Trial 1, Trial 2 and Trial 3, the Pre-Exercise (Pre-Ex) and Post-Exercise (Post-Ex) mean \pm SD of Perceived Fatigue and Perceived Recovery are shown. The Post-Exercise percentage change for each trial is also shown along with the average percentage change across the three trials.

	Trial 1			Trial 2			Trial 3			Average % change
	Pre-Ex	Post-Ex	% change	Pre-Ex	Post-Ex	% change	Pre-Ex	Post-Ex	% change	
Perceived Fatigue	2 \pm 1	6 \pm 1	38	2 \pm 1	5 \pm 2	35	2 \pm 1	6 \pm 2	33	35
Perceived Recovery	10 \pm 0	4 \pm 3	-256	10 \pm 0	4 \pm 2	-253	10 \pm 0	4 \pm 3	-268	-259

7.3.2 Evaluation of intervention (intervention x time)

Scrutiny of data histograms did not reveal gross deviation from normality although there was a significant difference between the mean and median data (Shapiro-Wilk $p > 0.05$) for PF. For PF and PR ANOVA (3x3) revealed a main effect of time ($p < .01$), no significant main effect of intervention ($p > 0.05$) and no significant time intervention interaction ($p > 0.05$). Ratings of PF and PR in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions are illustrated in Figure 7.1 and Figure 7.2.

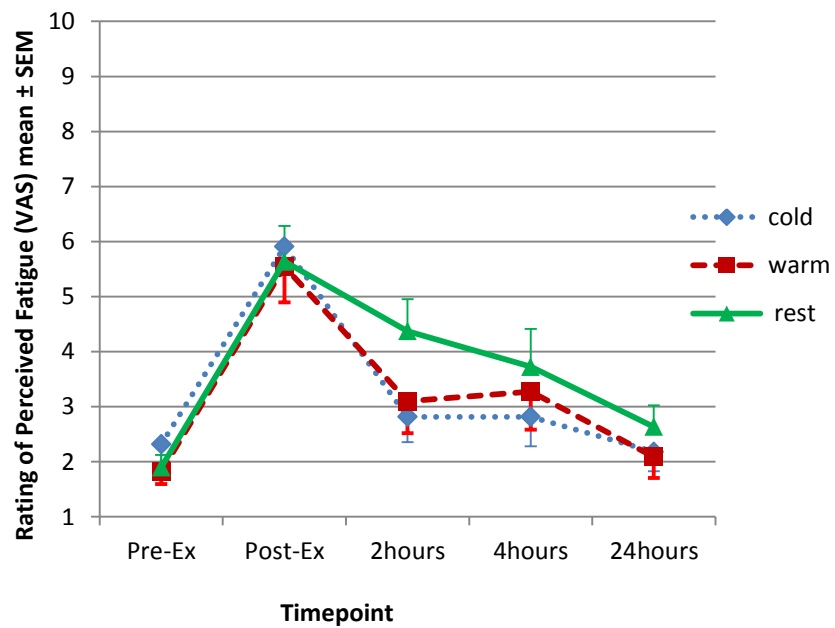


Figure 7.1 Rating of Perceived Fatigue (PF) in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

Rating of Perceived Fatigue mean \pm SEM for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- \blacksquare -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Pre-Exercise (Pre-Ex), Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

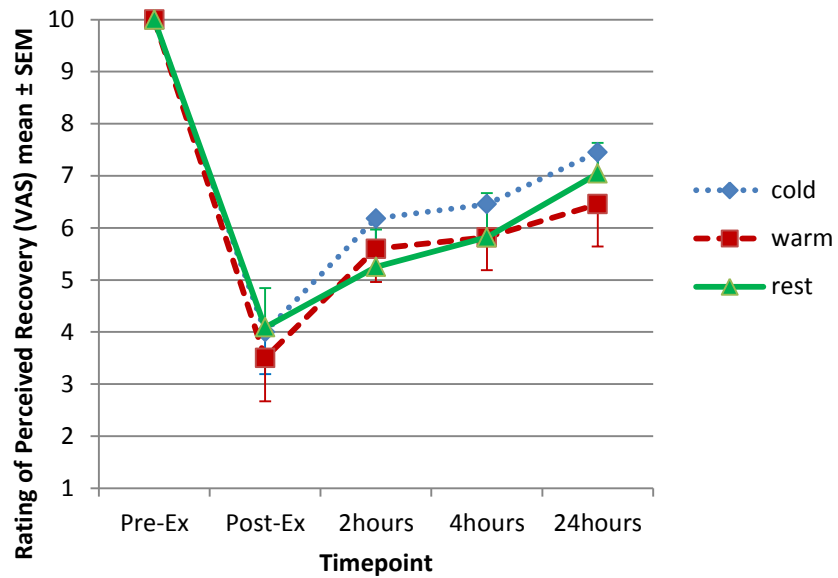


Figure 7.2 Rating of Perceived Recovery (PR) in trials of 5 minutes of cold water immersion, warm water immersion and rest recovery interventions

Rating of Perceived Recovery mean \pm SEM for trials involving cold water immersion ($\cdots\blacklozenge\cdots$ dotted line; diamond markers), warm water immersion ($- \blacksquare -$ dashed line; square markers) and rest ($- \blacktriangle -$ unbroken line; triangle markers), at time-points Pre-Exercise (Pre-Ex), Post Exercise (Post-Ex), 2 hours, 4 hours & 24 hours post exercise.

Warm water immersion was the most preferred recovery intervention (55%), followed by no preference (27%) and cold water immersion (18%). No participants preferred rest, which was also the least preferred (46%) recovery intervention. Figure 7.3 illustrates the percentage distribution of the nominated Preferred and Least Preferred recovery interventions.

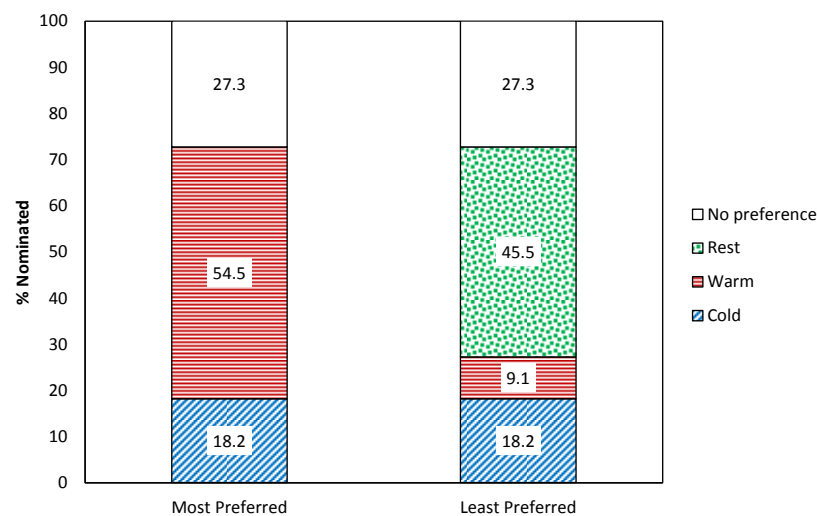






Figure 7.3 Percentage (%) distribution of nominated Preferred and Least Preferred recovery interventions of 5 minutes cold water immersion, warm water immersion and rest

The percentage distribution (%) of nominated Most Preferred and Least Preferred recovery interventions is illustrated of interventions: 5 minutes cold water immersion ( diagonal line), warm water immersion ( horizontal line) and rest ( confetti). No nominated preference is represented by  (no fill).

7.4 Discussion

These results suggest that most athletes prefer to engage in water immersion recovery interventions over passive rest, and that they will nominate a specific preference of warm or cold temperature. There was no significant main effect of water immersion on PF or PR, although at every post-intervention time-point higher average PF followed rest; and lower average PF and higher average PR followed cold water immersion.

Further research could substantiate this trend as the suggestion that water immersion could be beneficial to perceived fatigue and recovery was consistent with nominated preferred and least preferred interventions. Water immersion was strongly favoured as the preferred recovery intervention. Given the choice of interventions in this project, a total of 73% nominated a preference for water immersion with none preferring passive rest. Rest was also clearly the least preferred (46%) recovery intervention. This convincingly demonstrated a preference for “something over nothing”.

Cold water immersion was equally nominated as preferred or least preferred intervention (18%). While cold water immersion was perceived as ‘most beneficial’ by some athletes, it could have been an uncomfortable and stressful experience for others. Warm water immersion was the most preferred intervention (55%), and very few nominated this as the

least preferred intervention (9%). It is likely that warm water immersion was perceived as beneficial without the negative experience presented by immersion in colder temperatures.

Conclusions pertaining to preference are indicative given the choice of three specific test protocols: 5 minutes of warm or cold water immersion to the neck, and passive rest. This project did not evaluate athlete preference for alternative recovery interventions. Exploring athlete preference, and the rationale, for recovery agendas and interventions in a broader scheme is an area for further research.

The Noakes et al., (2005) definition of fatigue incorporates a conscious perception and interpretation, influenced by expectations and past experiences. Recruiting accustomed subjects, the familiarisation process and cross over design of this study sought to neutralise any effect of previous individual experience on overall results. However it is possible that the familiarisation experience contributed to athletes' perception ratings or their decision regarding intervention preference. The consistent rating of '10' for Pre-Exercise PR could have been misleading as PF ratings were not reciprocally zero. Nevertheless, the Pre-Exercise time-point did not influence the analysis of intervention effects, which was pre-planned to post-intervention time-points.

Exercise intensity and performance self-satisfaction have been proposed as a source of psychological stress post rugby match (Suzuki et al., 2004). The LIST replicated physiological challenges of game sports with consistent sprint performance across trials (Refer 4.6.2.1 LIST Performance) providing a stable measure of fatigue, however it was administered in a non-competitive environment which did not account for performance-related psychological stress. Athlete fatigue accumulates with prolonged SNS stimulation (Reilly & Ekblom, 2005), which could be reflected in PF and PR measures. Sympathetic arousal could be directly measured in future studies, particularly in a post-competition rather than research environment.

7.5 Chapter summary

Warm water immersion was the most preferred recovery intervention and passive rest was the least preferred of the test interventions. Cold water immersion was nominated with equal frequency as most preferred or least preferred recovery condition. While not statistically significant, at all time-points lower PF and higher PR ratings generally followed cold water immersion; and higher PF followed rest. This trend is worthy of further research as it was consistent with nominated preferred and least preferred interventions.

Chapter 8 STUDY 3: WATER IMMERSION IN ATHLETE RECOVERY - APPLIED PRACTICE IN THE HIGH PERFORMANCE ENVIRONMENT

8.1 Introduction

The intention of this section is to establish the implications of this project on water immersion recovery practice. All available information must be consolidated to answer the practice focussed question: is it worthwhile for athletes to engage in cold or warm water immersion recovery practices? This chapter explores expert opinion on current water immersion practice alongside how practitioners value and apply the scientific evidence.

Application of research findings to practice

In sports science and medicine, clinical practice often precedes research (Amonette et al., 2010). Innovative interventions are developed upon theoretical benefits, initiating anecdotal evidence and research seeking to substantiate the underpinning effects and efficacy. Water immersion is one example of this. The ultimate aim of sport science research is to improve sport performance and as such a key focus of research must be the applicability of findings to practice and specifically the target population (Bishop, 2008).

Sackett et al., (1996) define evidence based practice as “the conscious, explicit and judicious use of current best evidence in making decisions” (p71) which includes evidence from systematic research and clinical expertise gained through experience. Evidence based practice is characterised by a hierarchy of evidence categories (Amonette et al., 2010), which recognises the different information sources and their value in underpinning practice. Given the mixed results of previous research and the paucity of evidence supporting water immersion practice (Chapter 2), how the evidence is valued and applied is particularly important.

There are many factors which influence the application of research to practice. It is interesting to consider ‘how certain’ research findings have to be before they influence practice. Bishop (2008) acknowledges that interventions that do not have an effect under tightly controlled experimental conditions are unlikely to have an effect in the real world where many variables and factors interact. From this perspective, the statistically non-significant patterns observed in this study do not strongly advocate the use of water immersion in athlete recovery. However a minor incremental benefit is perceived by many in elite sport as the potential difference between success and failure. Although establishing statistical significance is a cornerstone of research and practitioners have a responsibility to ground advice in evidence (Amonette et al., 2010), it is reasonable to suggest that a benefit of *any size* is clinically meaningful to the high performance athlete.

Generalisation of water immersion practice

Interventions in science and medicine in sport should be objective driven with clear aims. This demands distinguishing athlete needs and objectives in different circumstances, such as

training and competition or across sporting disciplines. Training bouts are specifically designed to induce controlled, selective fatigue and adaptation; the objective of recovery interventions may therefore be to limit excessive damage and facilitate subsequent training session intensity, while promoting adaptive processes. It is anecdotally speculated that 'effective' recovery interventions could attenuate training adaptations. This study did not evaluate adaptive processes, however differentiation between training and competition settings is an important component of practice recommendations.

Research evaluating water immersion recovery interventions involve a variety of exercise protocols and settings and there is a tendency to extrapolate these findings to different sporting settings. As physiological responses are exercise dependent (Pedersen et al., 1998; St. Pierre Schneider & Tiidus, 2007) this should be done with caution. This study replicated the practice setting and demands on athletes as closely as possible, whilst maintaining scientific rigour and controlled trial conditions. The narrowly defined homogeneous target population in a cross over design with a control condition, advocated by Bishop (2008), allows the results of this study to confidently inform the practice of trained athletes following intense shuttle running exercise typical of game-sports.

However, the validity of extrapolating findings across sports is worthy of exploration given the paucity of evidence supporting water immersion recovery practice. There are parallels in the post-exercise responses of land-based exercise and swimming (Ferrer, Tauler, Sureda, Tur & Pons, 2009). Although research results should not be zealously generalised, this suggests they could be sensibly applied across sports with different exercise patterns.

8.2 Aim and objectives

The aim was to explore current practice and the decision making process of a small group of experts advising high performance athletes on water immersion recovery.

The objectives were:

1. To explore current water immersion practice of high performance athletes, and the rationale
2. To explore how evidence relating to water immersion recovery practice is valued and applied by practice experts
3. To formulate water immersion practice recommendations based on the findings of this study

8.3 Method

A purposive sample of eight professionals advising professional athletes on water immersion practice were provided with a research brief of this project in advance of a scribed, confidential semi-structured interview discussing their water immersion practice. Since this project explored current opinion in a domain undergoing continual discussion and development, it was conducted over a defined three week period.

8.3.1 Participants

A purposive, theoretical sampling approach, in the form of expert consultation, was designed to strategically correspond with the research questions (Bryman, 2004) and participants were selected based on specific criteria (Thatcher, Thatcher, Day, Portas & Hood, 2009). Participants were of the professional capacity to advise athletes on water immersion recovery practice, with a minimum of 5 years experience working with internationally competing athletes. Participants were of Sports Coach, Strength and Conditioning Coach or Sports Physiotherapist professional disciplines, and several also had relevant postgraduate research and teaching experience. To minimise homogenous opinion within the expert group, invited participants differed in profession, international location and sporting disciplines. Table 8.1 describes the characteristics of consulted experts.

Table 8.1 Characteristics of consulted experts

Professional characteristics of the 8 consulted experts are shown. Participants were categorised firstly according to their primary professional discipline, followed by secondary professional discipline and postgraduate research experience where appropriate. To demonstrate multiplicity of experts' background, their home country, country of current practice and involvement in professional sporting disciplines are shown.

Expert	Professional discipline		Research Experience	Home country	Current location	Manage professional athletes in sports of:							
	Primary	Secondary				1	2	3	4	5	6	7	8
1	Sports Coach	Operations Manager	Contributer (athlete cooling)	Aus	Italy	Cycling	Multi-sport						
2				UK	UK	Swimming							
3				UK	UK	Swimming	Modern Pentathlon						
4	Strength & Conditioning Coach (S&C)	Sports Coach	Professional Doctorate candidate	UK	UK	Beach Volleyball	Judo	Bobsleigh	Rugby				
5			MPhil candidate	UK	UK	Bob-skeleton	Tennis	Netball					
6	Sports Physiotherapist (SP)	Strength & Conditioning Coach; MSc Teaching	MSc (SP, S&C)	Aus	Italy, UK	Rugby - union & league	Football	Taikwondo	Squash	Athletics	Cycling	Rowing	Kayaking
7		MSc Teaching	MSc (SP, Recovery modalities)	UK	UK	Rugby	Boxing	Football					
8		MSc Teaching		NZ	UK	Rugby	Football	Bob-skeleton	Swimming	Basketball			

Although data were coded and interviews were confidential, all participants explicitly indicated anonymity was not necessary. This enabled expert profiles and opinions to be reported in their entirety, including reference to specific sports, which could otherwise have compromised their identity. The participant profile and sporting context is directly relevant to the validity of opinion in underpinning practice recommendations in the high performance environment.

8.3.2 Research brief

Participants were emailed a research brief of this project which presented an introduction, methodology and summary of results presented in Chapter 5, Chapter 6 and Chapter 7. To maximise the opportunity for independent interpretation of observations and minimise information selection biasing opinion, the research brief reported a full spectrum of results, graphical presentation of raw data and statistical tests without account for multiple comparisons. The intention was to present a transparent but structured report of this project, entailing an equivalent time commitment to reading and reflecting on a typical peer reviewed journal article. Therefore some general interpretations and initial responses to research questions of this project were also presented. This provided impetus for critique and independent interpretation of practice implications. The research brief is contained in Appendix 3.

8.3.3 Interview

Interviews were conducted 1-5 days after provision of the research brief via telephone, Skype or in person. The first intention was to establish experts' current water immersion practice and their rationale. The second intention was to canvas an interpretation of observations in this study, and identify potential implications this would have on their practice. The interview was semi-structured to facilitate discussion of common themes, identification of emerging issues and closure on viewpoints. The common interview format is contained in Appendix 4, and the following is an overview of the interview agenda:

- Your current advice to athletes on water immersion recovery
- The reasons underpinning your advice
- Your views on the research brief
- Identify & discuss emerging issues
- Further research questions
- Closure on key viewpoints

This qualitative approach sought to provide the most information relating to the aims of this study and the target group; the athletic performance recovery of trained high performance athletes who are regular users of water immersion.

8.3.4 Analysis

Data were analysed in a thematic analysis approach as described by Braun & Clarke (2006) with a sample size reaching theoretical saturation (Bryman, 2004; Thatcher et al., 2009).

8.4 Results

8.4.1 Key themes underpinning recommendations for water immersion practice

Experts recommend water immersion in athlete recovery primarily based on what individual athletes feel works for them. This was important as athletes were thought likely to respond differently. “How it feels” was a key determinant of preference.

“So I’ll say to an athlete, if you find it works go for it. But I don’t think it’s something they should have to do. If the athletes want it, give it to them.”

“Everyone is different. You can’t use data from someone else’s project and transfer it to you with different athletes. I don’t see how it would make sense.”

“We need to match up the exercise, the recovery and the athlete. The response is so varied in athletes.”

“We use warm water and stretching. It’s like stretching with your tracksuit on, it’s nice and warm. Swimmers are in the water all the time, and do I want to get wet again. It’s different if you’ve been for a run and are hot and sweaty and burning, it feels nice to sit in a cold bath for the cooling effect. Then it feels nice when you get back in the warm after cool. Then it feels like you’re doing something.”

“Aggressive contact sports like cold, its soothing from being in the cold.”

“Athletes like the feeling of warm-cold. Its more about what they feel.”

In making practice recommendations primarily on athlete preference, experts indicated a trust in the athletes’ opinion of what works best for them. Athlete expectation and compliance were also important.

“The ones that have done it often enough know whether it works.”

“Ultimately when it comes down to it even if you have a straight line on every graph, if your athlete chooses it then isn’t that enough of a reason, and consistently.”

“If it’s what the athlete wants it doesn’t make any difference.”

“It’s what works for the athlete, what they enjoy doing, athletes come from clubs that have done it and they say what works for them.”

“Athletes tend not to do things that are unpleasant, they don’t buy into it if it’s a hassle unless it really works.”

“They always seem to prefer it than nothing. Experience, the overwhelming thing was that athletes did not like not having it. Some athletes you have to talk them into anything but those same athletes moaning when they don’t have it, regardless of the physiology.”

A recurring theme was the lack of evidence supporting the practice of water immersion in athlete recovery. From this emerged a trend to seek expert opinion and consult sources other than published research in order to best inform practice.

"I can't really base it on science as there is so many mixed messages."

"I'm confused by the research."

"Probably a combination of things. The research that I've read and expert opinions. So I speak to the physiologist to see what the current thinking is. [researcher] is now saying you do whatever the athlete feels is right for them."

"I've known [researchers], I've had a lot to do with hot and cold therapy over the years. I've had cyclists involved in studies. The other thing I've had is [athlete] champion in the time trial. Pre-cooling him, by that stage we were using slushies and cold towels, stuff like that."

"My brother in law rode with a doctor and he asked him what he thought."

"I have definitely read a decent amount of stuff when I first started using them. But now it's more about what people say. Every time I look again there's been more intervention studies done but it's not more useful than what the athletes are saying and coaches saying that affects performance."

The evidence is not strong enough to impose water immersion on athletes who do not like it and activities with more certain outcomes must be a priority. Water immersion should be balanced with athletes' other commitments and the spectrum of things that influence performance, particularly exercise training programmes. It is also about having time.

"Other things are more important, sleep, rest, going home to rest, things that are nothing to do with swimming, uni work, that could be more of a priority. But I would use it as frequently as I could. There are so many things that influence athlete performance."

"I don't necessarily think I would enforce an ice-bath if we were travelling away from home and got home 5 hours after the match. But I definitely book a place with a pool. No doubt there is a logistical and pragmatic approach you've got to take. If I thought it would make a massive performance impact I probably would. But I'm just not convinced it makes that much of a difference to really go that far out of my way."

"Given the choice of sleep or water immersion I'd take sleep every time."

"If there's no effect....on tour the bobsleigh athletes go, to the ice, break the ice, go to all that trouble and its tiring....go to all that trouble at the expense of the athletes after a hard day, they just want to get back to the hotel to rest and eat."

"...I think before we use water immersion are they doing the basics outside of that well. Are they resting well, nutrition, cooling down properly, taking care of selfCertainly for athletes that are learning I massively emphasise that. And then obviously I still want to use water immersion."

"Generally it's probably not one of my priorities. Recovery is quite high on my list. I am still undecided what the best protocol is but I know I can affect their nutrition and placing training sessions in the right place in the week I know I will have an effect."

Even though water immersion was not the highest in priority in an athlete schedule, in a competitive environment experts want to be doing everything possible to facilitate performance. Something is better than nothing. It's also about being a professional and actively focussing on your recovery.

"It's about what you can sell to them [the athletes] as a coach. It feels like you're doing something professional. Good recovery habits develop, especially in young athletes. Even if its not hydro, it could be stretching."

"I don't know if particularly they work, but we're doing everything. You just want to be doing something more than what someone else is doing. Doing all the things you can, if there's the slightest chance there's any benefit you might as well do it."

"In my club we weren't allowed to have a control, it doesn't work practically in elite sport. People are happy to try something different but not prepared to do nothing at all. Not doing anything is the worst thing you can do. That's the danger of allowing people to go for the intervention that definitely doesn't work."

"I use warm as an opportunity to do some stretches and mobilisation not because I think it aids recovery, just using the time and opportunity to have a recovery environment and they can concentrate on what they are trying to recover. So get them in there to concentrate."

Despite open discussion of the lack of supporting evidence and athlete preference being the key definer of practice, experts would prefer to have their advice underpinned by scientific evidence.

"I must have read 40 odd articles about it. Something is better than nothing. It would be nice to know what that something is. We still remain unconvinced."

"I have to be pretty certain but don't need a test to show me that. I could get that from watching the athletes every day. But the benefit of having the sport science and sports medicine backup; I don't have time to do as much reading as I'd like."

Understanding the speculative mechanism of effect was very important to experts and evident in their justification of current practice. Experts' were not precise in engaging athletes in a specific water immersion protocol, indicated by their expression and use of varied protocols.

"If I had all the facilities, I would use a contrast protocol. I'd start with something like 30:30 seconds alternating 3 times, then increase the cold with experience, to a 3:1 ratio. I believe it should do something to the tissues in that time."

"..... I think I've been using 2 minute immersions based on a few things I've read. I would like a model of how long you have to be immersed to get a temperature change at every tissue level. The really skinny guys can't tolerate longer than 2 minutes. In terms of how long they spend in the warm, how long does it take to get you warm again? I pretty much double the time in warm, for no great reason. But they need to warm up again from a cooled state then stay in long enough to have some benefit otherwise there's no point."

"Usually 15-20 minutes of exercise in the water at low threshold intensity. Walking. Basically I want to get the hydrostatic pressure effect. Cold, 2-5 minutes depending on the person and tolerance level. In the past

I've used a contrast bath 2 to 1, 45 seconds cold, 90 seconds warm. So I suppose it depends on the effect I'm trying to get."

"I think cold water is probably good of your training or competing in the heat just to cool down. Whether its hot or cold, they usually have a really nice sleep after cold. So I believe that. I do think that sleep they have after it. I can imagine why it would work, the body shuts down like a bear going into hibernation."

"Warm I quite like the way the relaxation it might bring. I quite like the cold, the pumping rather than the sitting in the cold for 5-10minutes. At the moment I go with 5 minutes in the warm and dynamic movement. 2-3 minutes in the cold times 3-4 minimum. Finishing on cold is what I've tended to go with. I finish on cold, my understanding is you want to leave the vessels vasoconstricted. So the final pump is getting the toxins out."

"I guess there's an argument for just generally icing in terms of icing something that's incurred microtears. In terms of icing a nerve that's been fatigued I don't know what the reasoning would be. There's nothing to flush out so that crosses off contrast. I'm not really sure what you're trying to effect in extreme neural fatigue by putting them in the ice. Can you propagate nerve stimulation after you've iced?"

There was mixed opinion regarding whether water immersion should be used differently during training and competition. It emerged that differences were based on resource availability and logistics as much as the proposed intervention effect.

"In a perfect world where I had everything, recovery is recovery, there's not really any difference between training and competition. I'm not convinced of the effects enough to say you need it more if you've worked harder. It's not prescriptive enough for that."

"I think there's a big difference in how I use it in competition and not. During pre-season and during the tour period.....I try and place it in the week where I can possibly enhance recovery for the rest of the week. Otherwise at the end of the week or I try and place it logically where it fits."

"If they had repeated competition within less than an hour I probably wouldn't be getting them in ice baths because I'd be worried about muscle function. Conversely the heat I'd be worried about getting them too much relaxation, hydration and switching off."

".....they find slight benefits so I'd say if the athlete wants to do it I'd support it. But I wouldn't spend hundreds and thousands on it. We're on the road a lot too so we don't have access to things like we do here. Cold showers."

".....on tour use contrast just for the sake of it not for any reason over the cold. Chatting with the coaches, certain venues have ice baths so they use that, some have warm baths so they use that, some have nothing so they set up cold and warm baths in each hotel room."

The psychology of recovery was important on several levels, and a key theme underpinning application of water immersion practice. There were mixed views about the importance of differentiating between psychological and physiological recovery.

"Maybe it just settles their own mind that they've done everything they possibly can. Physiology is not the only thing."

"What I think is myth and what's not. I think if you believe it works it does. I also believe that if they think they're being pampered."

"We want them to hurt, be mentally tough. We want them to realise they're training hard during main training without using recovery all the time to feel better."

"The coach says he doesn't notice any difference to performance but he notices and emotional difference to we use it as often as possible."

"I certainly think the psyche behind it is an important tool and such a powerful influence. Doing everything you possibly can helps the psyche and gives confidence which is what makes you perform as well as you can."

"Perceived fatigue and perceived recovery are very important as they can produce better performances... Even though you might feel sore you can still produce results. Mind over matter. The psyche is so important."

"That's a massive area the psychological recovery, if they feel they are more recovered that's enough. The flip side to that is someone can feel recovered but are not physiologically recovered. I don't know what the implications of that are."

"They can be ready to go again, but they can't go again."

There were differences in water immersion practice between sporting disciplines. The rationale was analytical, based on athlete preference in that sport and justified by a desired, but speculative, mechanism of effect.

"I use water immersion during pre-season when we're doing dry land training. You're more sore after impact than swimming up and down so we use it then. The open water swimmers love to use it. But they swim for further for longer, it's a lot more intense. Pool swimmers race 200m and train 60 000, open water race 10km and do less than that in training so they use it then after the race."

"Water immersion and swimming, it would be more of a novelty going in cold. If you put them in warm water it wouldn't have any effect. The cold water produces results and has a novelty factor."

"I'm undecided as to how immersed I want them to be. Volleyball it's an opportunity to ice their shoulders, judo the majority of the load is on the upper body musculature. Bobsleigh is completely leg dominant so whether there is a need to put an athlete in up to their neck when it is so uncomfortable."

"Tennis is different to skelly as its longer duration and then you play again. With tennis you want to keep the muscles more relaxed so hot-cold or warm."

"To bring core temperature down before an event. Also after training in really hot conditions it takes a long time to feel good again. If you can cool down and have more time to recover in a normal range."

"Rugby and judo really appreciate it after competition which I would speculate is from a bruising point of view. Which is a different set of reasoning."

"Bobsleigh did just ice not contrast because they didn't want the flushing....I think about in judo flushing, so the contrast. Bobsleigh the cold. Volleyball it varies, some kind of active recovery, some kind of cold because they have impact, mostly it's about resource."

However, if the evidence was convincing it was agreed that regardless of the sport:

"Rate of recovery is recovery, from my point of view it doesn't make a difference what the sport is."

8.4.2 Response to the research brief

Experts agreed that the results of this project substantiate their current practice. The results support the continuation of water immersion recovery interventions with athlete preference as the key determining factor, and that it should not be prioritised above activities with more certain outcomes.

"It supports my opinion that literature doesn't give a gold standard approach. I think it supports my belief that you need to treat every individual as a different project. It had backed up my belief as to do what I do why I do."

"It [the research brief] backs up why I am not going to prioritise water immersion over other things such as nutrition, sleep and rest. It's good for coaches to know that."

"Key findings for me were that there were no real physiological outcomes which really supported the drive to go through water immersion. It's fine if you want to do it but equally fine if you don't."

"It didn't really enhance anything did it?"

"The biggest thing was the psychological response. They all preferred to do something. Whatever you use, even though resting is probably just as effective."

Although it confirms the mixed messages of previous research and the efficacy remains equivocal, the observations in this study were strong enough to influence the practice decisions.

"I get the feeling it seems to have an effect somewhere. I appreciate it doesn't have an effect on main variables but I get the feeling it did have an effect. Even when you have identified changes, differences and you can't say what the implications are its still telling you it does something. So it's better than nothing. When you can see a change you can explore it further. My general impression is warm water is better."

"Cold water might have a detrimental effect so that is a concern and is interesting especially if we're using it just for the hell of it."

"Reading your study makes me think that if I'm loading them in the gym or doing loads of jumps it would make sense for them to do some after gym. In reading other stuff it doesn't make sense to use it."

"The time-course of recovery.....showing the different points of recovery...the time of day, 2 sessions, that makes sense that that's recovered so I can push harder in that session."

"Looking through some of the graphs. CK, warm had the smallest change. I guess that comes back to it was better throughout following warm. Jump height had the least negative change after warm. Final output is jump height I guess which was worst with cold. Maybe you seize up, you might be able to get a better MVC after cold but as a whole body you might function better after warm."

"It's interesting how the immune system has spiked after cold; a stress response the body is so keen on. Is that good? Especially if you have a training session on the same day, you stress it once and then you stress it again."

This study highlights the complexity of deciphering the efficacy of water immersion recovery interventions; the mechanisms of effect and the application to practice. This research fulfilled a need to acknowledge this complexity and evaluate recovery using a spectrum of outcome measures. This enables practitioners to consider the evidence themselves when applying it to different practice scenarios.

"It reads well doesn't it? Even though it's mixed it's clear. You need to put the out the idea or concept and people can make up their own mind...You could focus on one thing if you want, but there's a lot there to decide on."

"My main thing from reading it was acknowledging the complexity of it rather than finding a significant conclusion which is quite rare. For practitioners so many of us make the mistake of applying significant findings that are only one thing. It was really useful having that kind of approach to applied research. That's how we have to investigate this stuff if we are going to use it in the real world. I did find it fairly complicated to read but that's why people make it simple but not useful. I think it was good to pull out the most relevant variables. Cold is detrimental but not on the most useful variables. It backs up why most of us are prioritising other things. I think we need to get a grip on recovery. Your study needs to be replicated about 20 times to make a matrix....your study ticks one of those boxes."

"It's good to see all the outcome measures, breaking it down into eccentric and concentric. You often only see 3 outcome measures. That's where we miss a lot on research is not breaking it down enough into components and then they say it doesn't work. For "a" sport one of those things might be beneficial."

"It was nice to see someone do something with a whole range of variables. It's nice to get into the whole psychology and performance. Most people only look at 3 or so things. It's nice to see....a standardised exercise including effort etcetera. It's nice to see a rest. A lot of the time they compare one against the other and say there's no difference which is useless."

Even though experts value this detailed scientific information in applying research to practice, they also valued the interpretation of meaning. This was consistent with the trend to seek expert opinion and consult sources other than published research in order to best inform practice.

"I'd like it in layman's terms."

"These tables are awesome with the interpretation and explanation."

"When you go through the graphs, it's nice to see the trends but the interpretation is helpful."

Further research questions identified by experts related to the relevance, validity and selection of outcome measures in determining the efficacy of water immersion in athlete recovery. This was consistent with the common theme of seeking to understand the mechanisms of effect.

"If someone can tell me about the mechanisms I'd use that back up. You know what the aim is and then you can apply it to practice."

"My final comment was.... do you think you've measured all the variables? Like cortisol and testosterone?"

"Did you look at core cooling?"

"Maybe that needs a blank page to the athlete, what do you like about it, look into that side of things."

"Oxygen re-supply, restocking the storage of oxygen and refuelling is more important than removing the waste."

"You can measure CK but you know what's going to happen. It will go up, they'll have it in their system. It's not a useful indicator. Some people write that CK in the blood means it's out of the muscle and ready to go again. You should measure muscle and blood CK. You could argue that high CK is actually clearance, that's a key question, what does it actually mean. If its (CK) irrelevant it makes the research irrelevant and if they've used it as an argument."

Experts agreed that the mechanism of effect and what water immersion is trying to achieve is a key concept underpinning practice, which is not adequately understood and contributes to the variety of protocols in current practice.

"I notice that you have the athletes immersed up to the neck which is how I would use the hot / cold / contrast intervention as I think of it as a whole body treatment involving core temperature. Many of the athletes and coaches think of it as treating the area that was fatigued.... many athletes (coaches) think that they are recovering the tired limbs...Like the football players wading in the surf. Many athletes only do the cold to the waist. Interesting. I notice that you use very cold water. We have our pools at 15 degrees and 38 degrees..... If you only had a tired toe, you'd only need to stick that in the pool."

8.5 Discussion

8.5.1 Implications for water immersion practice

The strong preference for water immersion suggests that water immersion in athlete recovery may be encouraged for athletes who perceive beneficial effects and that athlete preference should be the determinant of protocol.

The most convincing outcome of this study was the athlete preference for water immersion, particularly warm, leaving them "ready for participation in athletic activities at high intensity with maximal performance". This was consistent with expert opinion that water immersion should be applied based on what the athlete feels works for them, which is also favourable to compliance. How it feels and the psychological intention are particularly important meanwhile the proposed physiological effects remain unconvincing. There is some reservation about the possible detrimental effects of cold water immersion, although the evidence is not strong enough for this to take precedence over athlete preference.

It is important for professional athletes to undertake everything possible to facilitate performance. Experts agree that "something is better than nothing" in terms of water immersion based on the likelihood of physiological effects, positive influence on the psyche and the association with a professional approach to recovery. Through undertaking different

recovery interventions experienced athletes reach a sound understanding of “what works for them”, while this is an important development process for less experienced athletes.

However, prioritising and balancing different activities is grounded in the likelihood of benefit. Evidence surrounding water immersion is not convincing enough for athletes to forego interventions with more certain outcomes in favour of water immersion, such as nutritional restoration and rest. Although 5 minutes of water immersion seems a minimally imposing time commitment, logistics and provision of resources need to be factored into the athletes’ schedule.

Practice setting specificity – training, competition & sporting discipline

Water immersion protocols typical of current practice continue to entail a variety of temperatures, depths and durations. Practice advice varies between professionals, sporting disciplines, training phases and competition, and is largely underpinned by speculative mechanisms seeking to achieve a desired effect, for example body cooling, reduced inflammation, “flushing” or relaxing. Alongside athlete preference, resource availability is often the overarching deciding factor.

As demands on athletes are sport-specific, it is reasonable that the desired effect of water immersion recovery is also sport-specific. Furthermore, fatigue indices have different recovery time-courses and the results of this study suggest that warm and cold water immersion could affect this time-course differently. This has implications for the reasoning process and timing of the subsequent exercise bout. The absence of substantial effects of 5 minutes of water immersion in this study suggests it is unlikely to attenuate training adaptations. However the evidence is not strong enough to prescribe specific protocol in specific practice settings.

8.5.2 Application of research to practice

Experts use several levels of evidence to inform water immersion recovery practice, advocating a range of protocol grounded in several speculative mechanisms. While it is preferable that scientific evidence substantiates practice, it is complex to decipher practice implications from the mixed messages of systematic research and trials with varied protocols. This leads to practice decisions predominantly underpinned by experience alongside the appeal for further expert consultation.

Understanding the mechanisms of effect would best position experts to apply the research to individual athletes, sports and practice settings. This would facilitate definition of “best practice” water immersion protocol, which could be further defined by circumstances and resource availability.

It is a pitfall to make practice decisions based on research evaluating a narrow range of variables. While investigating isolated systems is essential to understanding fatigue and recovery mechanisms, fatigue and exercise performance are the constructs of integrated systems. Experts agreed that recommendations for practice and the underpinning evidence

must therefore also be multi-faceted. Particularly in team sports, the complex skills and decision making contributing to athletic performance are difficult to quantify. This study fulfilled a need to acknowledge this complexity and evaluate water immersion recovery using a spectrum of outcome measures. However, it is also possible that the efficacy of water immersion cannot be conclusively determined using the current spectrum of variables, and further exploration of performance related outcome measures may illuminate effects.

Bishop (2008) highlights the important stages in the research model to answer sports science questions as:

- defining the problem
- descriptive research
- predictors of performance
- experimental testing of predictors
- determinants of key performance predictors
- efficacy studies
- barriers to uptake
- implementing studies in the real sporting setting.

The desire to establish this all-encompassing evidence base perhaps contributes to generation of a body of varied rather than systematic research relating to recovery.

Experts' approach to water immersion recovery protocol is analytical, based on athlete preference in that sport and justified by a focussed, but speculative, mechanism of effect. More research is needed at the earlier stages of Bishop's (2008) model to define mechanisms of effect and more strongly underpin best practice guidelines for water immersion practice.

8.6 Chapter summary

Experts' approach to water immersion recovery protocol is analytical, based on athlete preference in that sport and justified by a focussed, but speculative, mechanism of effect. While research presents unconvincing and mixed messages, the strong athlete preference for water immersion suggests the practice should continue and that athlete preference should be the determinant of protocol. In the absence of scientific evidence, water immersion should not displace post-exercise activities with more certain outcomes.

Further research at several levels of pure and applied science is needed to justify and systemically influence water immersion practice in athlete recovery. Establishing the mechanisms of effect would be of particular value in informing decisions and applying research to different practice settings.

Experts agreed that this study fulfilled the need to acknowledge the complexity of deciphering the efficacy of water immersion recovery interventions; evaluation using a spectrum of outcome measures; the mechanisms of effect; and application to practice. The observations in this study were strong enough to influence practice decisions, supporting the continuation of water immersion recovery interventions with athlete preference as the key determining factor.

Chapter 9 GENERAL DISCUSSION - THE CONSTRUCTS OF RECOVERY, PERFORMANCE & PRACTICE

9.1 Introduction

The purpose of this chapter is to present and discuss the key project findings which underpin the response to the research questions and meaningfully contribute to this area of knowledge. Methodological considerations are intrinsic to the ensuing discussion of future research directions surrounding water immersion in athlete recovery. This then concludes the thesis.

Previous chapters presented circulating markers, functional and perceptual aspects of recovery separately, as isolating elements of the exercise response was helpful to explore interventions and their mechanism of effect in relation to the relevant literature. However, fatigue and exercise performance are constructs of integrated rather than independent systems (Hargreaves, 2008) and performance is unlikely the result of a single key variable (Barden & Kell, 2009). Investigation across a spectrum of outcome measures and scrutiny of their relative validity was necessary to form conclusions surrounding the efficacy of water immersion recovery practice.

Variables in this project were therefore categorised as main and exploratory variables, according to characteristics which determine their suitability to inform practice decisions. Without first establishing change over time in a dependent variable, it is difficult to argue that change seen post-intervention would be relevant (Atkinson, 2002). Therefore reliable, stable recovery indices which were sensitive to exercise and change over time arguably provided the most suitable measures to inform practice.

Statistical modelling is important to provide an accurate representation of 'the real world' (Field, 2005) and establishing statistical significance is a cornerstone of research. However it is imperative to distinguish statistical significance and clinical importance as phenomena that are not statistically significant may be clinically important and vice versa (Hudson, 2007). Although statistically significant findings provide the highest degree of certainty surrounding the effects of water immersion, findings of *likely* or even *possible* effects to athlete recovery are clinically relevant. This Chapter considers the scientific interpretation of water immersion efficacy alongside how the evidence is valued by practitioners (Chapter 8).

In a critical realist paradigm, this study sought to answer both scientific and practice questions. Data was therefore collated and examined with scientific rigour, and analysed with both research and practice perspectives. The clinical meaning of main variables was examined and clinically relevant patterns relating to the research questions were identified. The correlation between physiological, functional and measures of perception were explored as an important step in proposing the clinical relevance of scientific findings and making recommendations for practice.

9.2 General discussion and interpretation of key findings

9.2.1 Classification of main and exploratory variables

Evaluation of recovery using a spectrum of variables and several post-exercise time-points were strengths of this study (Chapter 8), but with consequences of multiple statistical comparisons and complexity in deciphering implications for practice. To manage the Type 1 error rate at the level of the variable, comparisons consistent with the hypothesis were pre-planned. To facilitate interpretation of practice implications and in response to research question *iv Of the spectrum of outcome measures, which are the most valued in informing practice decisions*, variables were organised into main and exploratory variables, according to sensitivity to post-exercise change and change over time.

Attributing change in a dependent variable to an intervention is difficult unless the variable changes over time without intervention (Atkinson, 2002). Therefore indices with a significant post-exercise decrement were categorised as main variables; considered the most suitable measures upon which to evaluate recovery. Without post-exercise change and a reasonably predictable recovery time-course it was difficult to attribute post-intervention changes to water immersion rather than biological variation or measurement error.

Several variables did not show a significant post-exercise decrement, but did have a main effect of time in the post-exercise time-course, raising the possibility that although there was no acute effect of exercise, there was a delayed exercise or intervention effect. The effect size of the LIST, or single exercise bout, could have been undetectably small, particularly in the population of trained athletes accustomed to repeated exercise bouts. Variables with no significant post-exercise change but a main effect of time in the post-intervention time-course ($p \leq .05$) were identified as exploratory variables. Variables with no main effect of time ($p > .05$) were unclassified. Table 9.1 presents a summary of statistical results, showing the classification of variables in relation to their sensitivity to change over time, the Pre-Post-Exercise change and significance of pre-planned statistical comparison for intervention effects.

Table 9.1 Summary of statistical results: classification of main and exploratory variables according to their sensitivity to change over time, Pre-Post Exercise change and significance of pre-planned statistical comparison for intervention effects

Variables with significant post-exercise change ($p \leq .05$) were classified as main variables. Variables with no significant post-exercise change but a main effect of time in the post-intervention time-course ($p \leq .05$) were classified as exploratory variables. Variables with no main effect of time ($p > .05$) were unclassified. The Pre-Post-Exercise change and significance of pre-planned comparisons for intervention effects is shown.

Variable classification	Recovery Variable	Pre-Post Exercise change		Post-intervention effects (2, 4 & 24 hour time-point analysis)			Pre-planned contrast	
		% change (average of trials)	Statistical significance <i>p</i> value	Main effect of Time	Main effect of Inter- vention	Time*Int interaction	Water immersion versus Control	Cold versus Warm water immersion
Main effect of time Pre-Post Exercise: Significant acute post-exercise change								
Main Variable	Leukocytes	↑ 39 ± 14	<i>p</i> =.02	Yes <i>p</i> <.01	No <i>p</i> =.11	Yes <i>p</i> =.04	At 24 hours <i>p</i> =.05; No with RHB correction <i>p</i> =.20	No <i>p</i> >.05
	Neutrophils	↑ 106±33	<i>p</i> =.01	Yes <i>p</i> <.01	No <i>p</i> =.66	No <i>p</i> =.28	-	-
	CK	↑ 90 ± 23	<i>p</i> <.01	No <i>p</i> =.36	No <i>p</i> =.72	No <i>p</i> =.37	-	-
	Myoglobin	↑445±150	<i>p</i> =.01	Yes <i>p</i> <.01	No <i>p</i> =.85	No <i>p</i> =.87	-	-
	KE peak torque	↓ 6 ± 4	<i>p</i> =.01	No <i>p</i> =.77	Yes <i>p</i> =.01	No <i>p</i> =.12	Yes <i>p</i> =.00	Yes <i>p</i> =.01
	KF peak torque	↓ 12 ± 3	<i>p</i> <.01	No <i>p</i> =.86	No <i>p</i> =.10	No <i>p</i> =.53	-	-
	Jump Work _{abs}	↓ 6 ± 2	<i>p</i> <.01	Yes <i>p</i> =.01	No <i>p</i> =.73	No <i>p</i> =.58	-	-
	Jump Work _{neg}	↓ 10 ± 3	<i>p</i> <.01	No <i>p</i> =.12	No <i>p</i> =.42	No <i>p</i> =.55	-	-
	Jump Peak Power _{neg}	↑ 11 ± 7	<i>p</i> =.04	No <i>p</i> =.26	No <i>p</i> =.61	No <i>p</i> =.50	-	-
	Hop Work _{abs}	↓ 6 ± 2	<i>p</i> =.01	No <i>p</i> =.09	No <i>p</i> =.93	No <i>p</i> =.87	-	-
	Perceived Fatigue	↑ 35	<i>p</i> <.01	Yes <i>p</i> <.01	No <i>p</i> =.27	No <i>p</i> =.90	-	-
	Perceived Recovery	↓ 259	<i>p</i> <.01	No <i>p</i> =.02	No <i>p</i> =.76	No <i>p</i> =.77	-	-
Main effect of time in the post-intervention time-course: Sensitive to change over time								
Exploratory variable	Lymphocytes	↓ 9 ± 7	No <i>p</i> =.08	Yes <i>p</i> =.02	Yes <i>p</i> =.01	No <i>p</i> =.20	<i>p</i> =.04; No with RHB correction <i>p</i> =.08	No <i>p</i> >.05
	Jump Height	↓ 2 ± 3	No	Yes <i>p</i> <.01	No <i>p</i> =.49	No <i>p</i> =.07	-	-
	Jump Flight Time	↓ 2 ± 2	No	Yes <i>p</i> =.01	No <i>p</i> =.48	No <i>p</i> =.07	-	-
	Reactive Index	↓ 2 ± 4	No	Yes <i>p</i> =.02	No <i>p</i> =.71	No <i>p</i> =.25	-	-
	Jump Work _{pos}	↓ 2 ± 3	No	Yes <i>p</i> <.01	No <i>p</i> =.51	No <i>p</i> =.07	-	-
	Jump Peak Power _{pos}	↓ 1 ± 4	No	Yes <i>p</i> <.01	No <i>p</i> =.18	No <i>p</i> =.29	-	-
	Hop Height	↓ 2 ± 3	No	Yes <i>p</i> =.01	No <i>p</i> =.46	No <i>p</i> =.63	-	-
	Hop Flight Time	↓ 1 ± 2	No	Yes <i>p</i> =.01	No <i>p</i> =.42	No <i>p</i> =.67	-	-
No main effect of time: Not sensitive to change over time								
Unclassified	Jump Contact Time	↑ 3 ± 4	No	No <i>p</i> =.08	No <i>p</i> =.89	No <i>p</i> =.31		
	Jump Work _{net}	↓ 18 ± 24	No	No <i>p</i> =.44	No <i>p</i> =.24	No <i>p</i> =.52		
	Hop Height (SD)	↑ 15 ± 22	No	No <i>p</i> =.54	No <i>p</i> =.37	No <i>p</i> =.37		
	Hop Contact Time	↑ 0.04 ± 3	No	No <i>p</i> =.90	No <i>p</i> =.52	No <i>p</i> =.25		
	Hop Contact Time (SD)	↓ 9 ± 13	No	No <i>p</i> =.76	No <i>p</i> =.43	No <i>p</i> =.38		
	Hop Flight Time (SD)	↑ 17 ± 20	No	No <i>p</i> =.56	No <i>p</i> =.37	No <i>p</i> =.37		
	Hop Displacement	↓ 1 ± 7	No	No <i>p</i> =.86	No <i>p</i> =.89	No <i>p</i> =.07		

9.2.2 Interpretation of intervention effects and potential clinical implications

The patterns of decreased lymphocytes following water immersion (refer Figure 5.3) and decreased leukocytes at 24 hours following water immersion (refer Figure 5.1) compared with the control condition of rest were not significant with correction for multiple comparisons. KE Peak Torque was significantly lower following water immersion compared with the control condition of rest ($p < .01$), and lower following cold water immersion compared with warm water immersion ($p = .01$) (refer Figure 6.9). The clinical implications of these observations are speculative, especially since there was no effect of intervention on any other variable ($p \geq .05$). Nevertheless in the critical realist paradigm, proposing potential clinical implications was relevant to explore the merits of future related research.

Decreased circulating lymphocytes could create vulnerability to infection (Braun & von Duvillard, 2004) and during strenuous or prolonged exercise a decrease in lymphocyte production of immunoglobulins could compromise cell-mediated immune responses (Gleeson, 2007). If decreased cell counts indicate impairment of the immune system and an 'open window' for infection, water immersion could be detrimental to recovery. Post exercise lymphocyte changes are largely attributed to T- and NK-cell subpopulations (Nieman et al., 1994) which orchestrate the inflammatory response via interleukin production (Kendall & Eston, 2002) and have been linked with overtraining and underperformance conditions (Robson, 2003). This project did not measure these cellular responses, but the potential cascade effect on athlete health positions it as a relevant area for further research.

Considering the relative influence of variables on athletic performance and their (construed) value to practitioners was also important in proposing the clinical relevance of scientific findings. Poor correlation has been observed between muscle soreness, muscle function and biochemical markers (Newham et al., 1987; Rodenburg et al., 1993; Thompson et al., 1999). Because of the uncertainty in correlating the histopathology of muscle damage with performance, functional measurement tools, particularly maximum voluntary contraction (MVC), are advocated for quantifying muscle injury and impairment (Warren et al., 1999).

KE Peak Torque was the only neuromuscular muscle function variable in this study with a detrimental effect of water immersion. With no measurable effect on Drop Jump or Repeated Hop skills, it is unclear whether this has implications for co-ordination or skill execution in the sports arena. The underpinning mechanisms do not rationalise a detrimental effect of thermo-neutral water immersion on muscle function, although the most likely explanation for cold water immersion-induced decrement in muscle function is cold impaired decrease in nerve conduction velocity (Algafly & George, 2007), which prolongs muscle action potentials (Evans et al., 1995) and depresses the myostatic reflex (Cross et al., 1996). Consequential delays in afferent and efferent neural pathways could be more evident in complex multi-skill sports technique which are neurally more complex than isometric contractions. Further research to substantiate this would be worthwhile as this would precipitate the advice to avoid cold water immersion prior to subsequent athletic participation.

Although desirable to directly evaluate performance 'global' measures involving co-ordination and skill execution are inherently more variable, as indicated in functional performance measures of this study (Chapter 6). Such measurement error could be considered

unacceptably high for clinical precision (Clark et al., 2002) and render it more difficult to show consistent results or significant effects. The correlation between the performance indicator Jump Height and KE Peak Torque, KF Peak Torque and Jump Work_{abs} (Chapter 6) was reasonable but supports use of a cohort of tests to inform clinical decision making.

The paucity of evidence validating physiological benefits of water immersion on athlete recovery suggests recovery is largely about perception. Does the physiological response *matter* if an athlete believes in an intervention or ‘feels better’ following it? Athlete preference was a determining factor of experts’ current water immersion practice, which was substantiated by the strong athlete preference for water immersion compared with rest in this project. Current thinking focuses on the interaction between mind and body (Beedie & Foad, 2009), therefore the relationship between athletes’ beliefs about recovery interventions and physiological measures must be scrutinised. Perceived recovery could validate non-statistically significant physiological and functional observations as treatment effects and preference are associated (Preference Collaborative Review Group, 2008). Although there was no statistically significant difference, higher average PR and lower average PF ratings followed cold water immersion at every time-point. Combined with an overwhelming athlete preference to engage water immersion over rest, this seems worthy of further investigation.

The central governor model allows the brain to respond to increasing perceived fatigue by increasing muscle fibre recruitment, effectively maintaining a similar output function (Noakes et al., 2005). This could explain the observed post-exercise changes in perceptual measures (and circulating markers of muscle damage in venous blood) alongside no significant change in several measures of muscle function. The physical expression and sensation of fatigue should be distinguished, and the sensory perception could be more relevant (Noakes et al., 2005). The “deliberate or inadvertent” use of the placebo effect could be advantageous to sport performance (Beedie & Foad, 2009) and several studies evaluating recovery modalities have made clinical recommendations based on perceived recovery in the absence of statistically significant physiological effects (Banfi et al., 2008; Banfi et al., 2007; Hemmings et al., 2000; Rowsell et al., 2009; Suzuki et al., 2004).

To this end, the clear preference for water immersion over passive rest indicated in this study and the value experts place on athlete preference positions water immersion as a worthwhile component to athlete recovery. Albeit, the questionable physiological benefits suggest water immersion – or an athlete preference for it - should not displace activities with more certain outcomes.

9.3 Summary of key findings

Table 9.2 summarises variables with an observed influence of water immersion.

Table 9.2 Observed influence of water immersion

Interpretation of the observed influence of water immersion on athlete recovery is shown for variables with a significant effect of intervention.

Variable	Interpretation
Leukocytes	Decreased venous leukocytes at 24 hours post-exercise were observed following water immersion compared to REST. This was most likely attributable to the observed decrease in venous lymphocytes. This difference was not statistically significant with correction for multiple comparisons.
Lymphocytes	Decreased venous lymphocytes were observed following water immersion compared to REST. This difference was not statistically significant with correction for multiple comparisons.
Knee Extension Peak Torque	Decreased KE Peak Torque was observed following water immersion compared to REST. This impairment was greater following COLD compared with WARM water immersion.

Key findings:

- Experts advise a variety of water immersion protocols in athlete recovery.
- The paucity of supporting evidence was acknowledged and practice is predominantly underpinned by athlete preference, speculative mechanisms of effect and resource availability.
- Establishing variables' change over time was important to plot the expected recovery time-course and evaluate the effects of an intervention.
- Significant post-exercise change was observed in variables venous leukocytes, neutrophils, CK, myoglobin; KE Peak Torque, KF Peak Torque, Jump Work_{abs}, Jump Work_{neg}, Jump Peak Power_{neg}, Hop Work_{abs}; PF and PR.
- Change over time in the recovery time-course was observed in variables venous lymphocytes, Jump Height, Jump Flight Time, Reactive Index, Jump Work_{pos}, Jump Peak Power_{pos}, Hop Height and Hop Flight Time.
- There was a significant time-intervention interaction for venous leukocytes, accounted for by the lymphocyte subpopulation. At 24 hours a decrease in venous leukocyte was observed following water immersion compared to the control condition of rest but this was not statistically significant.
- A decrease in venous lymphocytes was observed following water immersion compared to the control condition of rest but this was not statistically significant.
- There was a significant effect of intervention for KE Peak Torque, which was significantly lower following water immersion than rest and lower following cold compared with warm water immersion.
- There was no significant main effect of water immersion on athlete recovery on any other variable.

- Of the 3 test interventions in this project, warm water immersion was the most preferred recovery intervention and passive rest was the least preferred. Cold water immersion was nominated with equal frequency as most preferred or least preferred recovery condition.
- Given their significant post-exercise change and correlation with Jump Height, Jump Work_{abs}, KF Peak Torque & KE Peak Torque were the most reasonable functional performance indicators. Similarly Hop Work_{abs} was considered a reasonable indicator of Hop Height. Of the variable spectrum describing neuromuscular function, these were therefore considered most clinically relevant.
- Force plate data showed evidence that technique adaptations could compensate for fatigue-related changes in muscle function.
- There were multiple strong and moderate correlations between physiological, functional performance and perceptual measures. This outcome measure spectrum was therefore advocated as representative of the integrated constructs of fatigue and performance.

Possible effects of water immersion that would be clinically relevant:

- On average, improve perceived recovery and perceived fatigue followed water immersion at every time-point. This observed improvement was not statistically significant.

9.4 Response to research questions

i. What is the expected time-course of recovery without intervention?

There was an average 90% increase in venous CK Post-Exercise, followed by further increases of up to 200% at 4 hours. The venous myoglobin peak was immediately post-exercise and remained significantly elevated at 4 hours. The characteristic venous leukocytosis and neutrophilia peaked at 4 hours, which was probably superimposition of the acute and delayed leukocytosis.

Without intervention, venous neutrophils, CK and myoglobin had not returned to pre-exercise levels by 4 hours post-exercise, although all but CK had returned to pre-exercise levels by 24 hours. This suggests that the body had not completely returned to pre-exercise state for a subsequent same-day or morning following exercise bout.

Average Post-Exercise decrements of 12% in KF Peak Torque and 6% in KE Peak Torque were observed, substantiating the likelihood that muscle damage was induced in these muscle groups. KE Peak Torque was observed to have recovered at 2 hours while KF had not returned to Pre-Exercise levels at 24 hours.

There was an extremely small percentage change across all time-points in Jump Height, Jump Flight Time and Jump Contact Time. It is possible to conclude that Drop Jump performance was not affected by this exercise protocol, although it is more likely that athletes were able to compensate for fatigue related changes by altering their technique.

Significant post-exercise decrements were observed in Jump Work_{neg}, Jump Work_{abs} and Jump Peak Power_{neg} indicating a functional decrement specifically during the Drop Jump landing

phase. At 4 hours there was no remaining decrement in any variable, which on average was within 5% variation from Pre-Exercise performance. Hop Work_{abs} was the only variable describing Repeated Hop with significant Post-Exercise decrement, also greater than 5%, which did not persist at 2 hours post-exercise.

After seemingly having recovered at 2-4 hours, an emerging pattern of decline in next-day functional performance was observed in variables describing neuromuscular function. This indicates further evaluation of the recovery time-course of neuromuscular function would be worthwhile.

ii. Does 5 minutes of water immersion alter the expected time-course of recovery?

iii. Are there different effects of warm and cold water immersion?

5 minutes of cold or warm water immersion did not alter the time-course of venous CK, myoglobin and neutrophils over 24 hours compared to passive recovery. A pattern of reduced venous leukocytes, in particular the lymphocyte sub-population, followed water immersion compared to rest. This was not statistically significant and the implications on athlete performance are speculative.

Water immersion, particularly cold, impaired the recovery of KE Peak Torque. However the clinical relevance of this observation is unclear given the absence of measurable effect in any other neuromuscular function performance variable. While cold water immersion could retard neural conduction and explain a decreased MVC capacity, underpinning mechanisms do not rationalise a detrimental effect of warm water immersion on neuromuscular function.

The strongest finding was that of athlete preference. Of the three test interventions in this project, water immersion was indicated as preferable to passive rest, and warm water immersion was preferable to cold water immersion. Although not statistically significant, lower average PF and higher average PR ratings followed cold water immersion at every time-point.

The different recovery time-courses observed in the spectrum of variables could indicate different principle neural and systemic determinants, which water immersion and temperature could affect differently over time. It is possible that some potential underlying mechanisms are acute, while others manifest over a more prolonged time period. It is also possible that observations in this project were a product of natural variation, measurement error or chance. There remains the possibility that further effects are present but with an effect size too small to be detectable in the sample size of this project.

iv. Of the spectrum of outcome measures, which recovery measures best underpin practice decisions?

Changes in performance are unlikely the result of a single key variable (Barden & Kell, 2009). Using a spectrum of outcome measures to inform practice therefore has construct validity and further supports the argument for including measures of integrated functional outcome and

subsidiary components. Determining the clinical importance of research findings also included relative weighting of outcome measures within the spectrum. Grounding practice decisions requires selection of outcome measures from this spectrum that are reliable, valid and have the strongest relationship with athletic performance.

Change over time and post-exercise decrement was required to meaningfully plot the recovery time-course and interpret the effect of an intervention. Significant post-exercise decrement was observed in venous leukocytes, neutrophils, CK, myoglobin, KE Peak Torque, KF Peak Torque, Jump Work_{abs}, Jump Work_{neg}, Jump Peak Power_{neg}, Hop Work_{abs}, Perceived Recovery and Perceived Fatigue. Change over time in the recovery time-course was observed in venous lymphocytes, Jump Height, Jump Flight Time, Reactive Index, Jump Work_{pos}, Jump Peak Power_{pos}, Hop Height and Hop Flight Time. These variables were therefore given greater weighting in answering the research questions in this study.

Of the spectrum of outcome measures, Jump Height and Hop Height were considered the most direct measure of functional performance however there was not a significant post-exercise change. It is possible that only some elements of neuromuscular function contributing to functional performance were significantly affected by the LIST protocol, or that the effect size was statistically detectable in some but not all variables in this sample size. For this reason, investigation of subsidiary components was valuable, particularly alongside evidence to suggest they correlate with performance. There was correlation of Jump Height with Jump Work_{abs} ($r=.70$), KE Peak Torque ($r=.70$) and KF Peak Torque ($r=.51$) which were also sensitive measures of post-exercise decrement. KF Peak Torque provided a more consistent measure than KE Peak Torque. Hop Work_{abs} was similarly related to the performance measure Hop Height. These variables were therefore considered the most clinically relevant variables.

Although physiological response was important PF, PR and athlete preference were most valued by practitioners in informing water immersion practice. The prevalence of perceived benefits in this and previous studies and the absence of clear physiological benefits suggest future research focussing on perceived recovery is worthwhile.

Fatigue and recovery are multi-systemic and multi-factorial; integrating physiology, neuromuscular function, perception and athletic performance constructs. To provide the best advice to athletes, the effect of water immersion on these constructs must be understood independently and holistically. Multiple strong and moderate correlations between circulating markers, functional performance and perceptual measures of recovery confirm the outcome measures in this project provided a relevant spectrum representative of the integrated construct of fatigue and performance.

v. What are the recommendations for water immersion practice which stem from this study?

The outcomes of this study add to the current body of varied evidence which suggests that water immersion practice could be effective in facilitating recovery. The findings suggest that if

there is a physiological effect, it is likely to be small. However water immersion is a relatively accessible, non-invasive practice strongly favoured by athletes and supported by experts.

The test conditions replicated recovery protocol and conditions typically undertaken in the purpose build hydrotherapy facility at the University of Bath. Trained athletes utilising 5 minute water immersion to the neck should be confident that the outcomes of this study relate specifically to this facility. Table 9.3 contains a summary of the implications and practice recommendations stemming from this study, which were validated by expert opinion. Figure 9.1 presents a schematic application of this study design and results to water immersion practice.

Table 9.3 Summary of Practice Recommendations based on study findings

Practice recommendations stemming from key project findings are presented. These were validated by expert opinion.

Key finding	Implications	Practice recommendations
Experts advise a variety of water immersion protocols in athlete recovery. Advice is based on speculative mechanisms of effect, athlete preference and resource availability	There is a paucity of scientific evidence supporting the practice of water immersion in athlete recovery	<ul style="list-style-type: none"> Balanced assessment of water immersion resource costs and benefits should be undertaken
The physiological mechanisms and effect of water immersion on athlete recovery remain speculative	Evidence does not substantiate reports of performance benefit or attenuation of training adaptations	<ul style="list-style-type: none"> Water immersion, or an athlete preference for it, should not displace activities with more certain outcomes
Water immersion impaired the recovery of KE Peak Torque. This impairment was greater following cold water immersion	Water immersion could influence some elements of neuromuscular performance but is unlikely to have a large effect on athletic performance per se	<ul style="list-style-type: none"> Water immersion, particularly cold, closely preceding athletic participation should be engaged cautiously
Water immersion did not influence the recovery of any other neuromuscular performance indicator		<ul style="list-style-type: none"> Judicious and sensible application of water immersion in athlete recovery is unlikely to be detrimental to overall performance and holistic recovery
On average, water immersion appeared to improve perceived recovery and perceived fatigue	Water immersion could be beneficial to perceived recovery. If nothing else there could be a positive placebo benefit	<ul style="list-style-type: none"> Athlete preference is a reasonable component in determining water immersion recovery practice, including its application in training and competition settings
Athletes preferred to engage in water immersion recovery interventions over passive rest. Warm water immersion was more commonly preferred to cold water immersion		
Decreased leukocytes, accounted for by the lymphocyte subpopulation, followed water immersion compared to rest	The functional implications of this are unclear	<ul style="list-style-type: none"> Further research on larger subject numbers is required before influencing practice
Force plate data showed evidence that technique adaptations could compensate for fatigue-related changes in muscle function	Small effects will be difficult to identify in muscle function measures	<ul style="list-style-type: none"> Small effects of water immersion on performance would be difficult to quantify
There were multiple strong and moderate correlations between physiological, functional performance and perceptual measures.	This outcome measure spectrum was representative of fatigue and performance	---

Water immersion recovery in practice: study design and practice recommendations

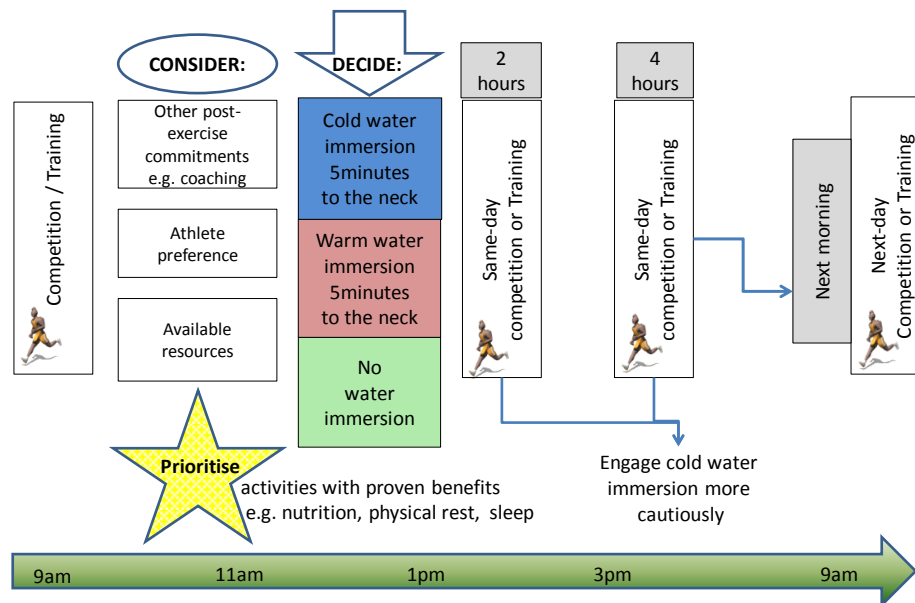


Figure 9.1 Schematic representation of application of study design & results to water immersion practice

A schematic representation of this project design is shown alongside an indicative timeline where athletes would likely participate in subsequent exercise bouts. Practice recommendations are annotated.

9.5 How this study has contributed to the knowledge base

Despite speculative effects on athlete recovery, water immersion durations in the order of five minutes are reportedly common practice (Peterson, 2006; Sellwood et al., 2007; Snelling, 2006). Therefore this project sought to determine the efficacy of cold and warm water immersion protocols of this duration. No previous studies have investigated the combination of conditions of this study; a controlled intense exercise bout replicating the demands of game-sports, immersion duration of 5 minutes, trained and familiarised athletes, in a cross over design including a control condition. Particularly, there has been no previous evaluation of this spectrum of variables and their inter-relationship.

Although the post-exercise time-course of circulating markers of muscle damage is well understood, this project illuminated the recovery time-course of a spectrum of further variables representing physiological, functional and perceived recovery.

The results of this project substantiate the position of current water immersion practice in athlete recovery: it is a commonly utilised intervention with a paucity of supporting scientific evidence and speculative mechanisms of effect. While the literature describes various but specific protocols (Chapter 2), expert consultation revealed non-systematic practice based primarily on athlete preference, perceived benefit and resource availability (Chapter 8). The overall results of this project support the continuation of water immersion recovery

interventions with athlete preference a reasonable contributing factor, and that it should not be prioritised above activities with more certain physiological outcomes.

This research fulfilled a need to acknowledge the complexity of water immersion practice and evaluate recovery using a spectrum of outcome measures. This enables practitioners to independently consider evidence in its greatest level of detail, which is valuable in an environment where clinical expertise strongly underpins application to different practice scenarios.

Although it confirms the mixed messages of previous research and the efficacy remains equivocal, the observations in this study were strong enough to influence water immersion practice decisions of experts in different sporting disciplines and different practice settings.

Specifically, this study used a narrowly defined subject population in a cross over design with a control condition. These results can confidently inform the practice of trained athletes utilising 5 minutes' water immersion to the neck in the purpose built hydrotherapy facility (cold water 8-9°C, warm water 32-37°C) at the University of Bath, particularly following intense shuttle running exercise typical of game-sports.

9.6 Methodological considerations and future directions

The body of research surrounding water immersion in athlete recovery appears to have answered some but not all questions. All studies remain defined by their exercise protocol and outcome measures, culminating in mixed implications for practice. The mechanisms of effect and the relationship of variables to athletic performance require further scrutiny before the efficacy of water immersion in athlete recovery can be substantiated.

Experts and sporting disciplines utilise a range of water immersion protocols, which is largely a product of speculative mechanisms of effect. The independent effects of water immersion and temperature over time need further delineation, and this should guide the further evaluation of commonly used water immersion protocols.

This project compared immersion to the neck in two specific water temperatures, broadly defined as warm and cold, with a control condition in a purpose-built facility. Since several effects of water immersion are temperature dependent, a spectrum of temperatures could influence on athlete recovery. However, with no difference established between extremes of warm and cold it seems unlikely that a precise ideal median temperature could be isolated.

Furthermore, conclusions relating to athlete preference for recovery intervention in this project were limited to the choice of test interventions: 5 minutes of warm or cold water immersion to the neck, and passive rest. Future research could explore and evaluate athlete preference, and the rationale, for alternative water immersion protocols, recovery agendas and interventions.

The evidence supporting tissue cooling following injury is not as judiciously applied as expected and there is not a dosage consensus (Bleakey, McDonough & MacAuley, 2004;

MacAuley, 2001), a similar weakness evident in the application of cold water recovery interventions. There is debate of the intention to attenuate the post-exercise inflammatory response versus impairing the cellular cascade adaptive processes. Until the optimal conditions for repair are defined, it is difficult to convincingly evaluate the efficacy of recovery interventions. Nevertheless, the balance of evidence suggests neither of these effects is likely with the short immersion times in the order of 5 minutes. If the aim is to achieve tissue cooling, evidence suggests that longer immersion times are required. If the aim is to influence the nervous system, more evidence is required to define the intentions and clarify the mechanisms.

It is not possible to determine which mechanism of action was attributable to the observations in this study. Further investigation with larger subject numbers could substantiate the observed influence of water immersion on the recovery pattern of main and exploratory variables in this project, or more closely investigate the related mechanisms. In the absence of statistically significant findings, it is a common pitfall to explore data for clinical relevance unrelated to the original research questions (Hudson, 2007), however the patterns identified in this study related to the original research questions of establishing the post-exercise time-course with and without water immersion intervention.

The post-exercise response and recovery time-course in this project followed the LIST exercise protocol. Although the LIST is consistent and reproducible, the typical fatigue pattern of shuttle running does not account for associated activities inherent to game sports such as ball skills, physical contact and multi-directional movements (Nicholas et al., 2000). It is reasonably assumed that these contribute to fatigue, and further challenge the recovery process. Once a post-exercise recovery time-course has been soundly modelled through controlled trials, further studies could evaluate the fatigue and recovery patterns in multi-skill settings. Whilst acknowledging the inherent variability in exercise intensity, this would further increase the external validity and applicability of results to competitive athletes in real-time situations.

Furthermore, it is well established that the post-exercise response differs following accustomed versus unaccustomed exercise (Blannin et al., 1996; McHugh, 2003; Newham, et al., 1987; Sacco & Jones, 1992; St. Pierre Schneider & Tiidus, 2007). Involving trained athletes in this project was crucial to the external validity however it could have increased the difficulty in showing significant results. It is also noteworthy that the protective effect of exposure to repeated exercise bouts is prevalent in blood measures (Newham et al., 1987) but not in protecting decline in contractile function (Clarkson & Ebbeling, 1988). Athletes in this study were familiar to all conditions of the study, eliminating the influence of the repeated bout effect.

There is a paucity of evidence to support water immersion in isolation and in conjunction with other recovery modalities. Experts recommend multi-faceted recovery practice including water immersion, compression garments, nutrition and hydration. Isolating the effects and benefits of individual modalities is important, but there is also the possibility that cumulative benefits offer the greatest influence to performance. Despite the pitfalls of evaluating modalities in conjunction before the underlying mechanisms of each have been fully understood, this may be helpful in demonstrating smaller effects and informing applied practice.

Individual participant characteristics could have interacted with the treatment in this project. Body mass index and inherent cold tolerance could conceivably influence response to cold water immersion, as could age, gender and circulatory conditions. Tissue temperature change is also influenced by many variables such as area of contact, subcutaneous fat, tissue conductivity and initial tissue temperature (MacAuley, 2001). Body composition however is unlikely to have influenced the results as the first few minutes of cooling are SNS mediated rather than a hypothermic response (Wilson et al., 2007). Nevertheless, it is difficult to measure and account for these variables in practice, and the large potential for individual and circumstantial variance must be considered.

Similarly, experts allude to athletes as individuals and profiling individual athletes in specific sporting disciplines, including their preference for recovery interventions, could be helpful in informing practice. Participants from this study were active in a range of sports and demands of different sports induce different post-exercise profiles (Mougios, 2007). This raises the possibility that optimal recovery strategies are also likely to be different.

This study evaluated the 24 hours post-exercise and it is possible that effects beyond this time-point were missed. It was undesirable to control the physical activity of athletes' in this study for a more prolonged period as it would have unduly disrupted training and competition commitments. Similarly, most athletes will be required to train or compete on the same or next day, so the 24 hours period of recovery was most clinically interesting.

Several studies have discussed the effect of residual fatigue accumulating across successive days of training or competition (Ronglan, Raastad & Borgensen, 2006; Spencer, Rechichi, Lawrence, Dawson, Bishop & Goodman, 2005). Whilst evaluation of fatigue and recovery over a relevant 24 hour period was central to the philosophy of this study, it was beyond the scope of the design to evaluate residual fatigue. The precise effects and mechanisms of recovery which follow a single exercise bout require further definition prior to drawing conclusions about residual fatigue.

Identifying a suitable spectrum of outcome measures to evaluate the efficacy of water immersion recovery interventions was challenging. Evaluating fatigue and recovery is underpinned by reliable measurement and meaningful correlations with the implications on athletic performance. The typical exercise response and recovery time-course was unclear in some variables of this project, rendering it difficult to interpret the effect of the intervention. Average percentage change data at 24 hours showed a decrement compared to Pre-Exercise in all neuromuscular function exploratory variables in all conditions. This suggests that recovery in these variables was generally not complete by the next day. This study therefore may not have captured the complete neuromuscular function recovery time-course which further research could more clearly delineate. The pattern of apparent recovery to a pre-exercise state followed by subsequent next-morning decline is also worthy of further investigation.

Exploratory variables were less sensitive to change over time compared to the main variables which showed post-exercise change and trended more predictably towards a pre-exercise state. Furthermore several of the exploratory variables are related, although the pattern of findings was consistent between MVC, Drop Jump and Repeated Hop skills.

The variability of measures in this study have been acknowledged, and could be problematic particularly in conjunction with the relatively small sample size. However, the repeated measures cross over design limited the influence of individuals' response, as does considering the spectrum of outcome measures when determining the overarching efficacy of water immersion on athlete recovery.

It is impossible to measure all (potentially) relevant outcome measures. Post exercise lymphocyte changes are largely attributed to T- and NK-cell subpopulations (Nieman et al., 1994) which were not measured in this project. This study did not evaluate the autonomic nervous system (ANS) which could be an area for further research. Since catecholamines (and other ANS neuropeptides and hormones) are likely to mediate immunological changes during exercise (Gleeson, 2007; Pedersen et al., 1998; Shepard, 2003) and influence neutrophil accumulation and leukocyte trafficking (St. Pierre Schneider & Tiidus, 2007), they are also likely to mediate these processes in recovery.

Indirect measures of muscle damage and recovery are common, however evaluation of architectural properties of muscle, myofibrillar and cytoskeletal responses would provide the most direct measures (Friden & Lieber, 1992). Evaluation at a cellular level would clarify the effect of reducing tissue temperature on hyperthermia-dependent training adaptations.

Consideration of animal models rather than human studies could enhance the understanding of recovery interventions on the cellular environment. Although compromising the external validity of applied science and medicine in sport, it may be the required step to clarify mechanisms of effect which is currently lacking in the knowledge base. This in turn would inform, direct and specify applied research in this area.

The search for minute and incremental benefits is inherent to research conducted in the athlete performance domain, with speculative mechanisms and perceived benefits sufficient to influence practice. However, this is juxtaposed with a body of experimental research involving sample sizes and statistical power designed to detect relatively large effects. It is difficult to attribute small percentage differences to an intervention if they are smaller than the typical measurement error or biological variation of performance-indicative outcome measures. The clinical relevance of a "one percent" advantage over an athletic opponent is self-stated, however the clinical relevance of a "one percent" change in a performance-related outcome measure is less assured. This project recruited a sample size sufficient to show a change of 20Nm in maximum peak torque production, which was considered the smallest worthwhile change unlikely to be a phenomenon of natural variation. The capacity to detect smaller potential effects of water immersion on athlete recovery was limited by this projected effect size, inherent variability of the outcome measures and would have required an impracticably large sample size for this project. Further research could target development and validation of performance-related outcome measures with extremely *low variability in the target athlete population*. This could facilitate the search for smaller effects in a targeted athlete population sample and better complement the precision sought in sports science and medicine.

9.7 Thesis conclusion

This project defined the expected post-exercise time-course of a spectrum of variables representing physiological, functional performance and perceived recovery in trained athletes. Several differences in the recovery time-course were evident between interventions, although further research is needed to establish the efficacy and mechanisms of effect of water immersion in athlete recovery.

Decreased KE Peak Torque was observed following water immersion compared to rest; and cold compared to warm water immersion. Observations of decreased venous leukocytes and lymphocytes following water immersion were not statistically significant. Although there was evidence of a detrimental effect of water immersion in one muscle function variable (KE Peak Torque), there was no detrimental effect observable in any other variable amid a broad spectrum representing physiological, functional and perceived recovery. It is therefore unclear whether this would impact athlete multi-skill performance substantially to warrant avoidance of water immersion. Judicious and sensible application of water immersion in athlete recovery is unlikely to be detrimental to overall performance and holistic recovery, however water immersion, particularly cold water immersion should be engaged cautiously closely preceding athletic participation.

In terms of feeling recovered and prepared for athletic performance, there was a strong athlete preference for water immersion over passive rest, and warm water was more often preferred than cold. Experts valued perceived recovery over equivocal physiological effects and recommend water immersion recovery interventions primarily based on “what the athlete feels works for them”, speculative mechanisms of effect and resource availability. These findings, combined with patterns of improved perceived recovery and perceived fatigue, substantiate the decision to engage water immersion in athlete recovery. With a paucity of evidence demonstrating substantial physiological effects, athlete preference is a reasonable consideration in determining water immersion practice.

Acknowledging the limitations in demonstrating physiological effects in this study and the detrimental effect observed in one variable (KE Peak Torque), the null hypothesis was rejected. Five minutes of warm or cold water immersion was valuable to overall athlete recovery from intense exercise. There was an overwhelming athlete preference to partake in water immersion compared to rest and an expert preference for athletes to actively engage recovery practices.

The spectrum of variables in this project was indicative of the complexity of this area of knowledge and the multitude of potential factors informing clinical decisions. The complexity of interpreting the results and deciphering practice implications was not unexpected, given the constructs of integrated physiology and athletic performance. It is possible that the efficacy of water immersion cannot be conclusively determined using the current spectrum of variables, and further exploration of mechanisms and performance related outcome measures may illuminate effects. Although the importance of non-significant observations should not be overstated, water immersion possibly influences the recovery time-course of venous lymphocytes and perceived recovery. There was evidence to suggest this influence is likely to be temperature-dependent. The results were not strong enough for the mechanism to be

clear, and the potential effects were too small to be confident of statistical significance in this subject population.

Although there was correlation between physiological recovery indices it is difficult to further extrapolate the implications for technique and athletic performance, where the effects are difficult to isolate. It is possible performance outcomes aren't yet able to be measured with an acceptable level of sensitivity or reliability to draw research conclusions.

The overwhelming athlete preference in favour of water immersion over passive rest and the unlikelihood of substantial detrimental effect suggests the practice should continue. In the absence of scientific evidence, water immersion should not displace post-exercise activities with more certain physiological outcomes.

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Appendix 1 - Within-subject maximum voluntary contraction (MVC) Knee Flexion Peak Torque at 20° – between-day mean and standard deviation

Table 10A1.1 Within-subject mean and standard deviation for isometric maximal voluntary contraction (MVC) Knee Flexion Peak Torque at 20°

Isometric maximum voluntary contraction (MVC) for Knee Flexion Peak Torque at 20° is shown for 12 participants in trials on consecutive days (Day 1 and Day 2). The between day difference is shown in N.m and as a percentage difference. The population sample mean and standard deviation are also shown.

Participant No.	MVC Day 1	MVC Day.2	Between-day difference	
			N.m	%
1	157	148	9	5.7
2	97	80	17	17.5
3	66	55	11	16.7
4	116	125	-9	-7.8
5	74	78	-4	-5.4
6	111	95	16	14.4
7	90	124	-34	-37.8
8	171	183	-12	-7.0
9	44	46	-2	-4.5
10	71	82	-11	-15.5
11	64	58	6	9.375
12	90	87	3	3.3
Mean	95.9	96.8	-0.8	-0.9
SD	37.9	40.9	14.5	38.2

Appendix 2 – Water immersion in athlete recovery (WIAR) project: record of intervention water temperatures

Table A2.1 Water immersion in athlete recovery (WIAR) project: record of intervention water temperatures

Cold and warm water temperature was measured at the start and end of each 5 minute immersion intervention. Start, end and mean temperatures for each participant are shown in degrees Celsius. The sample population range, mean and standard deviation (SD) are also shown.

Subject	Cold water			Warm water		
	Start	End	Mean	Start	End	Mean
WIAR_01	8	8	8	33	33	33
WIAR_02	9	9	9	35	35	35
WIAR_03	8	9	8.5	33	33	33
WIAR_04	9	9	9	35	35	35
WIAR_05	9	9	9	37	37	37
WIAR_06	9	9	9	36	36	36
WIAR_07	9	9	9	37	37	37
WIAR_08	9	9	9	37	37	37
WIAR_09	9	9	9	32	32	32
WIAR_10	8	9	8.5	35	35	35
WIAR_11	9	9	9	36	36	36
Range	Highest	9	9	9	37	37
	Lowest	8	8	8	32	32
Mean		8.7	8.9	8.8	35.1	35.1
SD		0.5	0.3	0.3	1.8	1.8

Appendix 3 – Expert consultation: Research brief

WATER IMMERSION & RECOVERY OF ATHLETIC PERFORMANCE: A MULTI-DISCIPLINARY, CRITICAL REALIST APPROACH TO INFORMING PRACTICE RESEARCH BRIEF

Author: Sonya Moore, Sports Physiotherapist, University of Bath

INTRODUCTION

High performance athletes undertake large exercise volumes which are associated with increased injury risks (Jones, Cowan & Knapik, 1994), fatigue and performance decline (Halson & Jeukendru, 2004) and immune suppression (Gleeson, 2007; Nieman & Pederson, 1999). The sport science and medicine community must therefore scrupulously manage training loads and recovery of athletes participating in intense and successive exercise bouts to realise both optimal training adaptations and peak physical condition.

Fatigue mechanisms and exercise performance limitations are multi-systemic and integrative, including systems physiology of neuromuscular activation, metabolism, temperature homeostasis, and the “psyche” (Hargreaves, 2008). Recovery is therefore measureable using an array of outcome measures representing muscle damage, inflammation, neuromuscular function and athletic performance. There are two defining elements of recovery: the restoration to the pre-exercise state of health and the time course over which this occurs.

Water immersion recovery interventions are aimed at enhancing athlete recovery from intense exercise. There is a body of mixed evidence comparing various subject populations, exercise scenarios, water immersion protocols (temperature and immersion time) and outcome measures. The mechanisms by which water immersion could affect recovery are speculative rather than established and the direct influence on athletic performance per se is difficult to quantify.

Key issues that make application of research findings to water immersion practice challenging:

1. Broad spectrum of water immersion temperatures (eg. cold, warm, contrast)
2. Evaluation following non-comparable exercise protocols (eg. eccentric vs aerobic exercise)
3. Use of untrained participants
4. Different water immersion protocols (ie. different intervention: immersion duration, depth)
5. Different outcome measures
6. Contradictory and varied findings
7. Mechanisms of effect are speculative rather than established

Aiming to inform current practice, this study investigated:

- the effects of 5 minutes water immersion;
- on blood markers of muscle damage, neuromuscular function, perceived and overall recovery;
- in trained subjects;
- following intense exercise replicating that of game-sport athletes.

METHOD

Participants

11 male athletes volunteered to participate in this study. They were athletes who habitually compete in high intensity exercise, and were regular users of water immersion recovery. Although this could have increased the challenge of demonstrating smaller effects, for application to the athletic community it was necessary to replicate this familiarity and test the efficacy in accustomed individuals.

Table 1: Characteristics of Participants

	Mean \pm SD	Range
Age (years)	20.3 \pm 2.5	18-26
Height (cm)	187.4 \pm 12.0	177.2 - 208.1
Weight (Kg)	81.3 \pm 8.3	67.2 - 97.4
Beep (shuttle level)	11.06 \pm 1.40	9.11 - 14.02
VO ₂ max (mL x kg ⁻¹ x min ⁻¹)	52.2 \pm 4.2	46.8 - 61.2

Test exercise

Participants completed the Loughborough Intermittent Shuttle Test (LIST): 90 minutes of shuttle running at intermittent speeds, consisting of 6x15 minute repeated cycles, interspersed with 3 minutes of rest. One cycle involved repeating the following 20m shuttle sequence 11 times:

walk	walk	walk	sprint	cruise	cruise	cruise	jog	jog	jog
------	------	------	--------	--------	--------	--------	-----	-----	-----

Within the 20 metre sprint shuttle, 15 metre sprint performance was measured using photocell timing gates (Newtest Powertiming System, Finland). Sprint performance was consistent between trials, and had declined significantly between the first and last LIST cycles. Rating of Perceived Exertion (RPE) was also consistent between trials.

Test interventions

The following were compared in a repeated measure randomised cross over design:

COLD: 5 minutes of water immersion to the neck, at 8.8 \pm 0.3°C

WARM: 5 minutes of water immersion to the neck, at 35.1 \pm 1.8°C

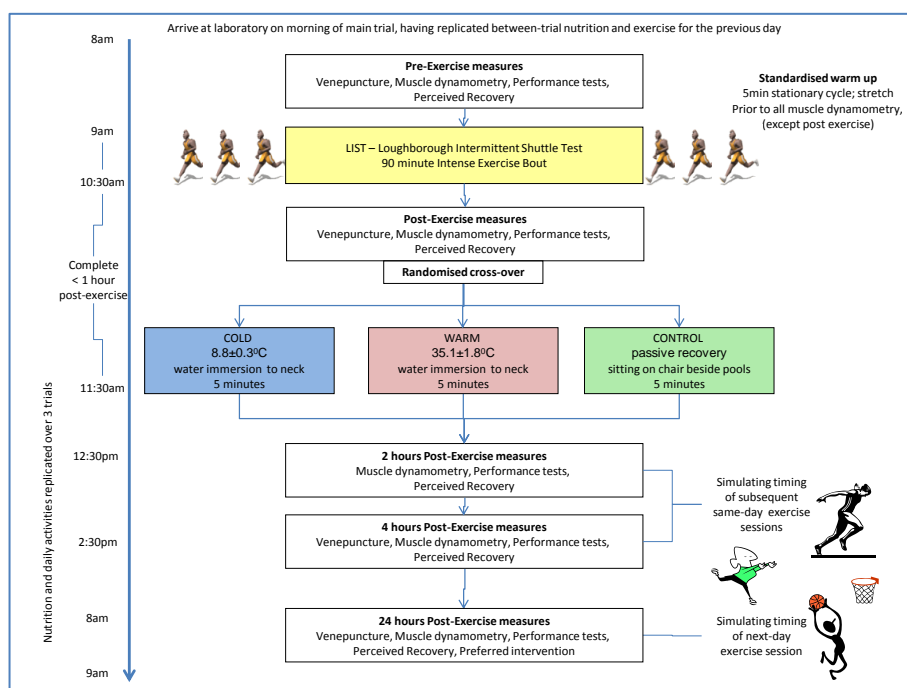
Control: 5 minutes of passive recovery, sitting on a chair next to the water immersion pools

The recovery intervention was completed within one hour of completing the exercise protocol, as this is the time frame that most closely replicates the typical activity of competitive athletes. Nutrition, hydration and activity levels were monitored, and were held consistent, over the 48 hours surrounding each trial.

Recovery outcome measures

Outcome measures were recorded Pre-Exercise, Post-Exercise, and at 2, 4 and 24 hours post exercise. These were time-points likely to coincide with participation in subsequent exercise bouts. Recovery was evaluated from analysis of venous blood indices of muscle damage and inflammation, neuromuscular function and perceived recovery. Figure 1 is a schematic representation of the study.

Figure 1: Schematic study design: Water immersion & recovery of athletic performance: a multi-disciplinary, critical realist approach to informing practice.



Further description of outcome measures

Muscle damage – venous blood

Leukocytes

Neutrophils

Lymphocytes

Creatine Kinase (CK)

Myoglobin

Subjects lay supine on a plinth for 15 minutes prior to venous blood sampling. This maintained consistent posture and immediate pre-sample behaviour between tests, avoiding confounding the results with orthostatic influences. Venous blood is more reflective of whole body responses than capillary blood, and was therefore the sample of choice.

Muscle force - Dynamometry

Knee Flexion (KF) Peak Torque
Knee Extension (KE) Peak Torque

Muscle dynamometry tested maximal isometric knee extension and knee flexion torque. Subjects performed 5x5 second isometric maximum voluntary contractions (iMVCs), with 10 seconds recovery between contractions, for each of KE at 60° and KF at 20°.

Neuromuscular performance – Force Plate

Drop Jump

Jump Height
Jump Flight Time
Jump Contact Time
Reactive Index (ratio of contact time to flight time)
Jump Work (neg, pos, net, abs)
Jump Peak power (neg, pos)

Subjects stood with two feet on a 30cm high box positioned at the front of the force plate. They were instructed to step off the box, leading with the same leg on each occasion, and jump as high as possible as quickly as possible from the force plate.

Repeated Single Leg Hop

Hop Height_{tot}
Hop Contact Time_{tot}
Hop Flight Time_{tot}
Landing Locus Displacement
Hop Work_{abs}

Subjects performed 6 successive hops on a force plate on their preferred leg. They were instructed to hop as high as possible, as quickly as possible and maintain the same position on the force plate.

Force plate data analysis

Post-exercise decrements were hypothesised in force production and capacity to decelerate and accelerate the centre of mass, resulting in reduced peak torque, jump height and hop height; increased contact time and hop landing locus displacement. However, longer contact times could enable generation of the same force albeit over a longer period of time and technique changes could compensate for fatigue, with or without a change in jump height. Variables that captured both force and time, and characteristics relating to mechanical efficiency were therefore explored. Eccentric (negative velocity – *neg*) and concentric (positive velocity – *pos*) contact time phases were differentiated as they have inherent mechanical differences and distinct muscular demands.

Explanation of the variable of work

Work represents the rate at which a force is applied, and was calculated as function of power and time. It represented the effort required to control the ground reaction force (GRF) acting on the centre of mass (CoM). $Work_{net}$ was defined as the sum of $Work_{neg}$ and $Work_{pos}$, representing the total work applied to the CoM to control the GRF during the contact phase. $Work_{abs}$ represented total work required to control the GRF acting on the CoM during the jump regardless of the direction in which that work was done. This variable was most representative of the overall force-over-time demand on the athlete to complete the drop jump for maximum height and rapid contact time.

Perceived recovery

Perceived Fatigue (PF)

Perceived Recovery (PR)

Preferred intervention

On a visual analogue scale of 1-10, subjects rated their Perceived Fatigue (PF) and Perceived Recovery (PR). At the end of the study, in terms of feeling most prepared for athletic performance, participants were asked if they had a preferred and least preferred intervention, and if so to nominate the preferred recovery condition.

SUMMARY OF RESULTS

Tables 2, 3 & 4 summarise the key findings. The level of statistical significance is included in these summaries to facilitate further interpretation of clinical relevance and practice implications.

ANOVA (2x3) comparing Pre- Post Exercise showed no trial order effect in any variable ($p > .05$). Variables with a main effect of time ($p \leq .05$) were identified, indicating significant post-exercise change. These were classified as main variables.

ANOVA (5x3) showed a significant effect of intervention and time-intervention interaction for KE Peak Torque ($p \leq .05$). There was no main effect of time ($p > .05$). Follow up t-tests showed that KE Peak Torque was significantly lower following warm and cold water immersion than rest at 2 and 4 hours ($p \leq .05$), and lower following cold water immersion at 24 hours ($p \leq .05$). Figure 7 illustrates the KE Peak Torque time-course.

ANOVA (5x3 or 4x3) showed no main effect of intervention on any other variable ($p \geq .05$). Variables with a main effect of time post-intervention were identified ($p \leq .05$) and were classified as exploratory variables. The post-exercise time-course of main and exploratory variables were plotted, with further statistical comparison to the Pre-Exercise state. These comparisons are presented in Tables 3 & 4.

There was a significant time-intervention interaction for leukocytes and lymphocytes ($p \leq .05$). Follow up t-tests revealed that leukocytes and lymphocytes were significantly decreased at 24 hours following warm water immersion ($p \leq .01$). Lymphocytes were significantly increased at 2 hours following cold water immersion ($p \leq .01$) and decreased following warm water immersion ($p \leq .05$). Figures 2 & 17 illustrates the leukocyte and lymphocyte time-course.

Table 2: Summary of variable post-exercise time-course without intervention (control)

	Variable change over time	Recovery Indicator	Pre-Post Exercise % change (av of trials)	Significance of Pre-Post Ex change	Different to Pre-Ex state:			Recovered to Pre-Ex state by:	
					2 hours	4 hours	24 hours		
No main effect of intervention (<i>p</i> > .05)	Main variables: Significant post-exercise change	Leukocytes	↑ 38.8 ± 13.8	<i>p</i> = .02	n/a	Yes <i>p</i> = .00	No <i>p</i> > .05	24 hours	
		Neutrophils	↑ 106.2 ± 32.7	<i>p</i> = .01	n/a	Yes <i>p</i> = .00	No <i>p</i> > .05	24 hours	
		CK	↑ 90.0 ± 22.8	<i>p</i> = .00	n/a	Yes <i>p</i> = .00	Yes <i>p</i> ≤ .01	Not by 24h	
		Myoglobin	↑ 445.3 ± 150.4	<i>p</i> = .01	n/a	Yes <i>p</i> = .00	No <i>p</i> > .05	24 hours	
		KF peak torque	↓ 11.9 ± 3.3	<i>p</i> ≤ .01	Yes <i>p</i> = .00	Yes <i>p</i> = .00	Yes <i>p</i> = .01	Not by 24h	
		Jump Work _{Kabs}	↓ 6.1 ± 1.7	<i>p</i> ≤ .06*	Yes <i>p</i> = .03	No <i>p</i> > .05	No <i>p</i> > .05	4 hours	
		Jump Work _{Kneg}	↓ 10.2 ± 2.5	<i>p</i> ≤ .02	Yes <i>p</i> = .04	No <i>p</i> > .05	No <i>p</i> = .05	4 hours	
		Hop Work _{Kabs}	↓ 6.3 ± 2.4	<i>p</i> ≤ .05	No <i>p</i> > .05	No <i>p</i> > .05	No <i>p</i> > .05	2 hours	
		Perceived Fatigue	↑ 34.1	<i>p</i> = .00	No <i>p</i> = .07*	No <i>p</i> = .03*	Yes <i>p</i> ≤ .01*	24 hours*	
	Perceived Recovery	↓ 261.0	<i>p</i> = .00	No <i>p</i> = .05*	Yes <i>p</i> ≤ .01*	Yes <i>p</i> = .00*	4 hours*		
	Change over time unclear	KE peak torque	↓ 5.7 ± 3.6	<i>p</i> ≤ .03	No <i>p</i> > .05	No <i>p</i> > .05	No <i>p</i> > .05	2 hours	
		Jump Peak Power _{neg}	↑ 10.5 ± 7.2	<i>p</i> > .05 n/s**	No effect of time over recovery time-course				
	Main effect of time over recovery time-course	Exploratory variables:	Lymphocytes	↓ 8.9 ± 7.0	n/s				
			Jump Height	↓ 2.3 ± 3	n/s				
			Flight Time	↓ 1.6 ± 1.6	n/s				
			Contact Time	↑ 2.5 ± 3.7	n/s				
			Reactive Index	↓ 2.1 ± 4.4	n/s				
			Jump Work _{Knet}	↓ 17.5 ± 24.0	n/s				
			Jump Work _{Kpos}	↓ 2.3 ± 3	n/s				
			Jump Peak Power _{pos}	↓ 0.9 ± 3.8	n/s				
			Hop Height	↓ 2.3 ± 2.9	n/s				
			Hop Flight Time	↓ 1.1 ± 1.6	n/s				
No significant change over time									
	Jump Work _{Knet}	↓ 17.5 ± 24.0							
	Hop Height (SD)	↑ 15.4 ± 21.8							
	Hop Contact Time	↑ 0.04 ± 3.1							
	Hop Contact Time (SD)	↓ 8.7 ± 12.6							
	Hop Flight Time (SD)	↑ 16.5 ± 20.2							
	Hop Displacement	↓ 1.2 ± 6.8							

*T1 $p = .00$, T2 $p = .06$, T3 $p = .00$; ** T1 $p = .16$, T2 $p = .39$, T3 $p = .00$

⁺Different to post ex

Strength of Significance p	
$\leq .01$	Accepted with Bonferroni correction for multiple comparisons
$\leq .05$	Accepted without Bonferroni correction for multiple comparisons

Main variables

Indices with a significant main effect of time and post-exercise decrement were categorised as main variables; considered the most suitable measures upon which to evaluate recovery. Without change over time or post-exercise change, it is difficult to argue that changes seen during water immersion recovery interventions would be relevant. Table 2 shows the post-exercise time course in these measures in the control condition of 'rest'. The recovery time-course for rest, cold water immersion and warm water immersion of selected variables are illustrated by Figures 2-13. Although there was no main effect of intervention for any variable and a time-intervention interaction only in Perceived Recovery and KE Peak Torque, Table 3 describes how water immersion intervention could have altered the recovery time-course.

Figure 2

Figure 3

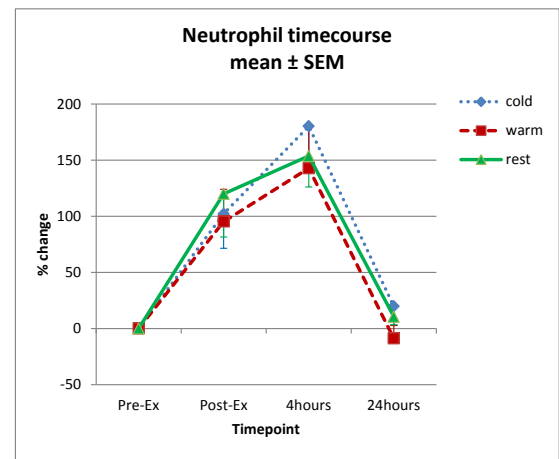
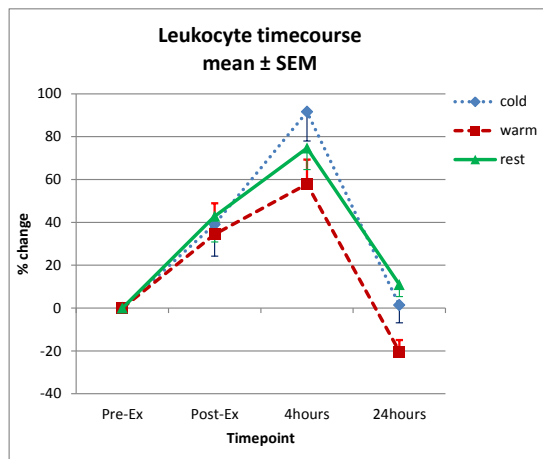


Figure 4

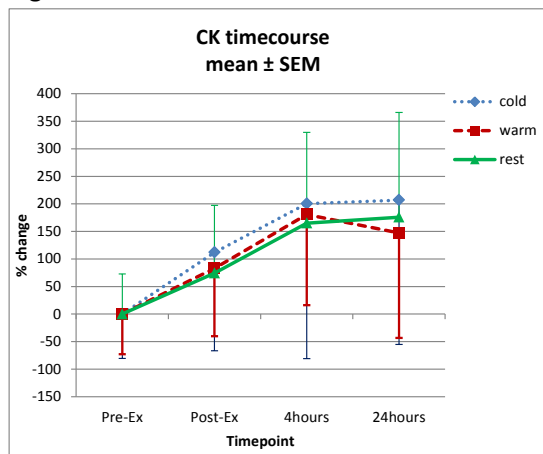


Figure 5

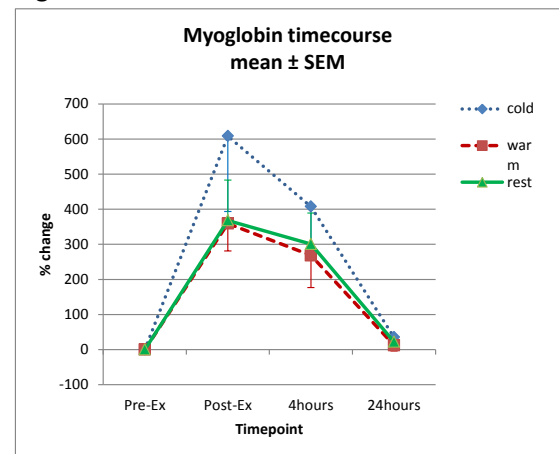


Figure 6

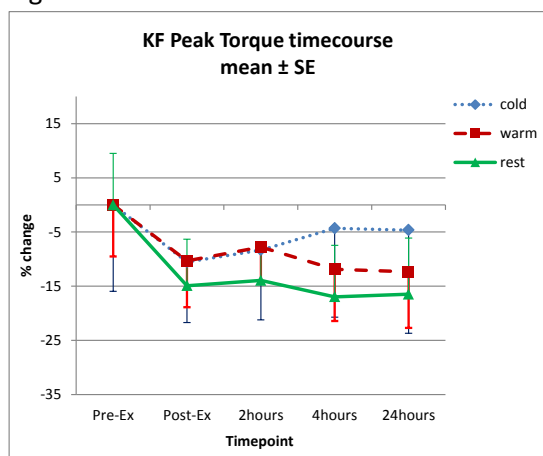


Figure 7

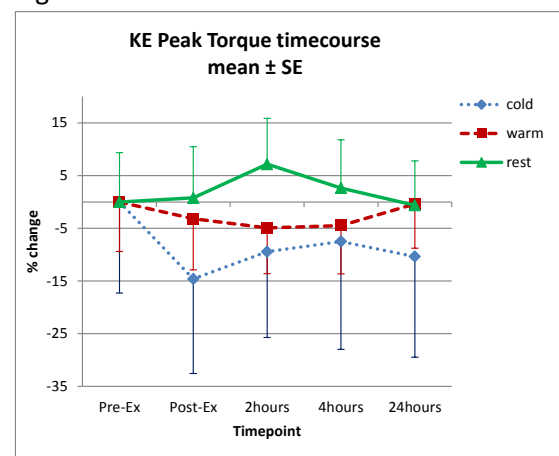


Figure 8

Figure 9

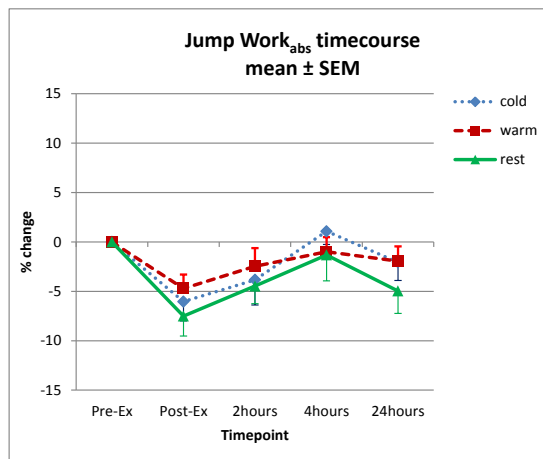


Figure 10

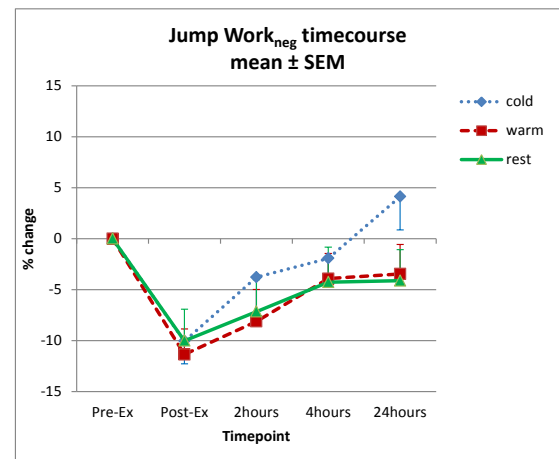


Figure 11

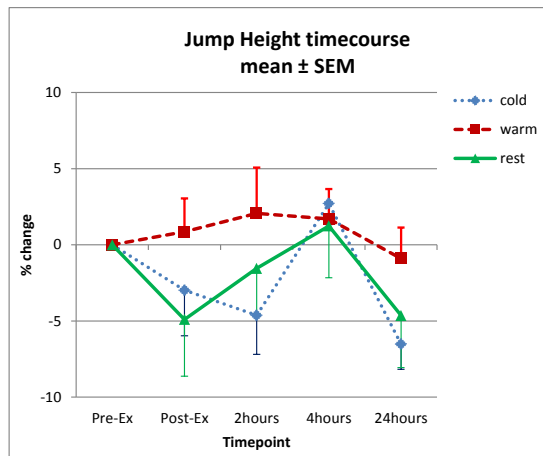


Figure 12

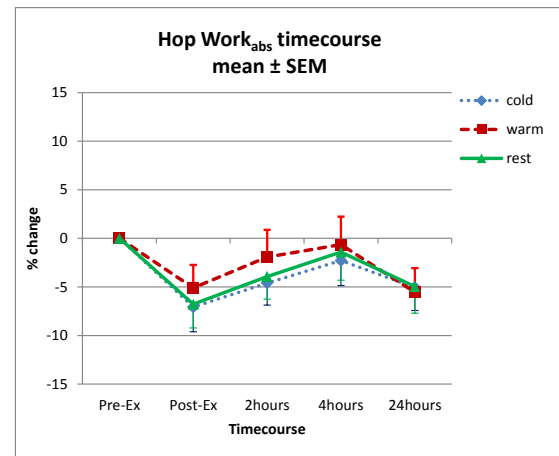


Figure 13

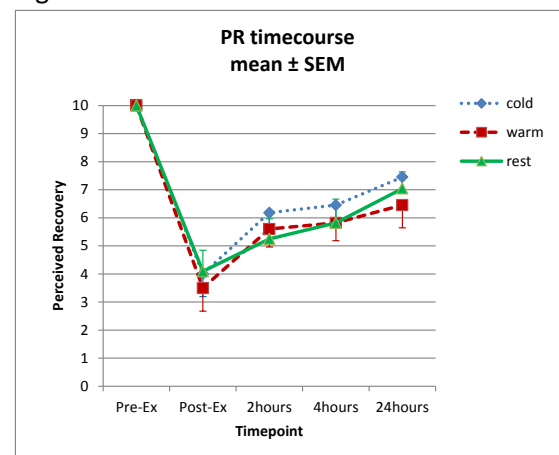
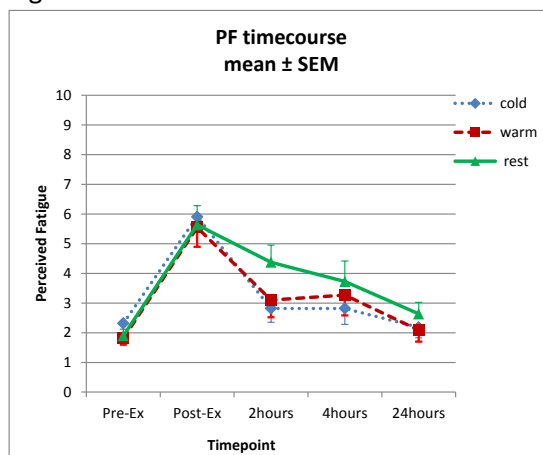


Table 3: Influence of water immersion on the post-exercise time-course of main variables

Variable	2 hours	4 hours	24 hours	Interpretation	Without intervention, recovered by:
Leukocytes	n/a	Sig diff to Pre-Ex in all conditions [Pre-ex-4 $p \leq .01$]	Water immersion different to REST: WARM with 99% certainty, COLD with >90% certainty [warm-rest $p = .01$ cold-rest $p = .07$]	Leukocyte levels at 24 hours post-exercise were decreased following water immersion; cold with 99% certainty and warm with >90% certainty. This was most likely attributable to the observed decrease in lymphocytes, at 24 hours post exercise, as neutrophils were not different to pre-exercise levels.	24 hours
Neutrophils	n/a	Sig diff to Pre-Ex in all conditions [Pre-ex-4 $p \leq .01$]	Not sig diff to Pre-Ex in all conditions [Pre-ex-24 $p > .05$]	Not influenced by water immersion	24 hours
CK	n/a	Sig diff to Pre-Ex in all conditions [Pre-ex-4 $p \leq .01$]	Sig diff to Pre-Ex in all conditions [Pre-ex-24 $p > .05$]	Not influenced by water immersion	Not by 24h
Myoglobin	n/a	Sig diff to Pre-Ex in all conditions [Pre-ex-4 $p \leq .01$]	Not sig diff to Pre-Ex in all conditions [Pre-ex-24 $p > .05$]	Not influenced by water immersion	24 hours
KF peak torque	Decrement remained following water immersion with 95% certainty. Decrement remained following REST with 99% certainty [Pre-ex-2 Cold $p = .02$ Warm $p = .05$ Rest $p = .00$]	Returned to pre-exercise levels following COLD. Decrement remained following WARM & REST with 99% certainty [Pre-ex-4 Warm $p = .01$ Rest $p = .00$]	Returned to pre-exercise levels following water immersion. [Pre-ex-24 Warm $p = .09$ Rest $p = .01$]	At 2 hours post-exercise, KF peak torque decrement remained with greater certainty following rest than following water immersion. At 4 hours post-exercise KF peak torque had returned to a Pre-Exercise state following COLD water immersion. At 24 hours post-exercise KF peak torque had returned to a Pre-Exercise state following water immersion.	Not by 24h
Jump Work _{abs}	Returned to pre-exercise levels following water immersion. Decrement remained following REST with >95% certainty [Pre-ex-2 Rest $p = .03$]	Sig diff to Pre-Ex in all conditions [Pre-ex-4 $p > .05$]	Returned to pre-exercise levels following water immersion. Decrement remained following REST with 95% certainty [Pre-ex-24 Rest $p = .05$]	At 2 hours and 24 hours post-exercise, the effort required during the drop jump was not different to Pre-Exercise following water immersion.	4 hours
Jump Work _{neg}	Returned to pre-exercise levels following COLD water immersion. Decrement remained following WARM and REST with >95% certainty [Pre-ex-2 Warm $p = .03$ Rest $p = .05$]	Sig diff to Pre-Ex in all conditions [Pre-ex-4 $p > .05$]	Sig diff to Pre-Ex in all conditions [Pre-ex-24 $p > .05$]	At 2 hours post exercise, effort required during the jump landing phase had returned to a pre-exercise state following COLD water immersion.	4 hours
Hop Work _{abs}	Returned to pre-exercise levels following WARM water immersion and REST. Decrement remained following COLD with >90%	Sig diff to Pre-Ex in all conditions [Pre-ex-4 $p > .05$]	Decrement remained in all conditions with 90% certainty. [Pre-ex-24 cold $p = .06$ warm $p = .05$ rest $p = .10$]	At 2 hours post exercise, return of the effort required during the repeated hop to a pre-exercise state could have been impaired following COLD water immersion. The indicative decrement remaining in all conditions at 24 hours post-exercise is inconsistent with other observations that Hop Work _{abs} recovered by 2 hours post-exercise without intervention and at 4 hours	2 hours

Variable	2 hours	4 hours	24 hours	Interpretation	Without intervention, recovered by:
	certainty [Pre-ex-2 Cold $p=.07$]			in all recovery conditions.	
Perceived Fatigue	Not different to post-exercise following REST. Reduced following water immersion with 99% certainty. [Post ex-2 warm & cold $p\leq.01$]	Reduced following water immersion with 99% certainty. Reduced following REST with >95% certainty. [Post ex-4 warm & cold $p\leq.01$; Rest $p=.03$]	Sig diff to post-exercise in all conditions ($p=.00$)	Post-exercise Perceived Fatigue was reduced at 2 hours following water immersion. Post-exercise Perceived fatigue was reduced with greater certainty following water immersion than REST at 4 hours. While not statistically significant at the 95% confidence interval, lower PF ratings generally followed COLD at 2, 4 & 24 hours.	24 hours
Perceived Recovery Sig time intervention interaction	Different to post-exercise following water immersion with 99% certainty. Different to post-exercise following REST with 95% certainty [Post ex-2 warm & cold $p\leq.01$; rest $p=.05$]	Sig diff to post-exercise in all conditions ($p\leq.01$)	Sig diff to post-exercise in all conditions ($p\leq.01$)	Post-exercise Perceived Recovery was increased at 2 hours following water immersion. While not statistically significant at the 95% confidence interval, higher PR ratings generally followed COLD at 2, 4 & 24 hours.	4 hours
KE peak torque ¹ Sig time intervention interaction	Water immersion different to REST with >95% certainty [Cold-rest $p=.01$; Warm-rest $p=.03$]	Water immersion different to REST with >95% certainty [Cold-rest $p=.02$; Warm-rest $p=.01$]	COLD different to WARM with >95% certainty [Cold-warm $p=.02$]	There was greater post-exercise decrement of KE Peak Torque following water immersion compared to REST at 2 & 4 hours post-exercise. This impairment could have persisted for 24 hours following COLD compared with WARM water immersion.	2 hours

¹KE peak torque did not provide a stable measure upon which to judge intervention efficacy with certainty. There was no main effect of time. Although an average post-exercise decrement of 6% across trials was observed, the post exercise response was inconsistent & was observed to decline or improve. This inconsistency was not observed in other outcome measures.

Significance p
≤ 0.01 Accepted with Bonferroni correction for multiple comparisons
≤ 0.05 Accepted without Bonferroni correction
≤ 0.10 Not statistically significant but would be clinically relevant

Observations suggest that several variables representing neuromuscular function returned to pre-exercise levels more quickly following water immersion, particularly cold. In the control condition, Jump Work_{abs} and Jump Work_{neg} decrements remained at 2 hours post-exercise and had resolved at 4 hours. At 2 hours, there was no Jump Work_{abs} decrement following water immersion and no Jump Work_{neg} decrement following cold water immersion. KF Peak Torque had not returned to Pre-Exercise levels at 24 hours in the control condition, and had returned at 4 hours following cold and 24 hours following warm and cold water immersion. PR was increased at 2 hours following water immersion, accompanied by decreased PF. Higher average PR and lower average PF ratings followed cold water immersion at every time-point.

It was possible that water immersion impaired the recovery of KE Peak Torque at 2 and 4 hours post-exercise and this impairment persisted for 24 hours following cold water immersion. However the relevance of this observation is unclear as KE Peak Torque did not provide a stable measure upon which to judge intervention efficacy with certainty. There was no main

effect of time. Although an average post-exercise decrement of 6% across trials was observed, the post exercise response was inconsistent & was observed to decline or improve. This inconsistency was not observed in other outcome measures. The underpinning mechanisms do not rationalise a detrimental effect of thermo-neutral water immersion.

The post-exercise time-course of neutrophils, CK and myoglobin were not influenced by water immersion.

Exploratory variables

Several variables did not show a significant post-exercise decrement, but did have a main effect of time in the post-exercise time-course (Table 2), raising the possibility that although there was no effect of exercise, the recovery intervention had an effect (or consequence). The nature of this change over time was therefore further explored for clinical relevance and informing further research. Identifiable recovery patterns and implications are described in Table 4.

Table 4: Possible influence of water immersion on the recovery time-course of exploratory variables

	Post-Exercise time-point				
	2 hours	4 hours	24 hours		
Variable	Relevant statistical finding & % difference to Pre-ex	Relevant statistical finding & % difference to Pre-ex	Relevant statistical finding	% difference to Pre-ex	Interpretation
Lymphocytes		warm-rest $p=.04$; cold-rest $p=.01$	Pre-ex-24 warm $p=.01$		With 99% certainty, compared to Pre-exercise, Lymphocytes were decreased at 24 hours following warm water immersion. At 4 hours Post-exercise, Lymphocytes were increased compared to rest with 99% certainty following cold water immersion and decreased with 95% certainty following warm water immersion.
Jump Height	Pre-ex-2 cold $p=.10$	Pre-ex-4 cold $p=.08$	Pre-ex-24 cold $p=.00$	COLD ↓6.5% WARM ↓0.9% REST ↓4.6%	With 99% certainty, compared to Pre-exercise, Jump Height and Jump Flight Time were decreased at 24 hours following cold water immersion.
Jump Flight Time	Pre-ex-2 cold $p=.10$	Pre-ex-4 cold $p=.08$	Pre-ex-24 cold $p=.00$	COLD ↓3.4% WARM ↓0.5% REST ↓2.5%	With ≥ 90% certainty, compared to Pre-exercise, Jump Height and Jump Flight Time were decreased at 2 and 4 hours following cold water immersion.
Jump Contact Time		Pre-ex-4 rest $p=.09$	Pre-ex-24 cold $p=.08$ rest $p=.00$	COLD ↑5.9% WARM ↑8.7% REST ↑13.4%	With 99% certainty, compared to Pre-exercise, Jump Contact Time was increased at 24 hours following rest. With ≥ 90% certainty, compared to Pre-exercise, Jump Contact Time was increased at 4 hours following rest and 24 hours following cold.
Reactive Index			Pre-ex-24 cold $p=.01$ rest $p=.00$	COLD ↓8.1% WARM ↓5.3% REST ↓13.0%	With 99% certainty, compared to Pre-exercise, Reactive Index was decreased at 24 hours following cold water immersion and rest.
Jump Work _{pos}		Pre-ex-4	Pre-ex-24	COLD ↓6.4%	With 99% certainty, compared to Pre-exercise,

	Post-Exercise time-point				
	2 hours	4 hours	24 hours		
Variable	Relevant statistical finding & % difference to Pre-ex	Relevant statistical finding & % difference to Pre-ex	Relevant statistical finding	% difference to Pre-ex	Interpretation
		cold $p=.07$	rest $p=.00$	WARM ↓0.9% REST ↓4.5%	Jump Work _{pos} was decreased at 24 hours following rest. With ≥ 90% certainty, compared to Pre-exercise, Jump Work _{pos} was decreased at 4 hours following cold water immersion.
Jump Peak Power _{pos}	Pre-ex-2 warm $p=.07$		Pre-ex-2 rest $p=.01$	COLD ↓4.1% WARM ↓1.0% REST ↓9.7%	With 99% certainty, compared to Pre-exercise, Jump Peak Power _{pos} was decreased at 24 hours following rest. With ≥ 90% certainty, compared to Pre-exercise, Jump Peak Power _{pos} was decreased at 2 hours following warm water immersion.
Hop Height	Pre-ex-2 cold $p=.01$ COLD ↓6.8% WARM ↓0.1% REST ↓5.8%		Pre-ex-24 cold $p=.01$ warm $p=.05$ rest $p=.08$	COLD ↓7.4% WARM ↓5.8% REST ↓5.5%	With 99% certainty, compared to Pre-exercise, Hop Height and Hop Flight Time were decreased at 2 and 24 hours following cold water immersion. With ≥ 90% certainty, compared to Pre-exercise, Hop Height was decreased at 24 hours in all conditions; and at 24 hours following water immersion.
Hop Flight Time	Pre-ex-2 cold $p=.01$ COLD ↓3.5% WARM ↓0.1% REST ↓0.9%		Pre-ex-24 cold $p=.01$ warm $p=.06$	COLD ↓3.9% WARM ↓3.0% REST ↓2.4%	

Significance p
≤ 0.01 Accepted with Bonferroni correction for multiple comparisons
≤ 0.05 Accepted without Bonferroni correction
≤ 0.10 Not statistically significant but would be clinically relevant

Average percentage change data at 24 hours showed a decrement compared to Pre-Exercise in all neuromuscular function exploratory variables in all conditions, illustrated in Figures 14, 15 & 16, suggesting that recovery in these variables was generally not complete by the next day. This study therefore may not have captured the complete neuromuscular function recovery time-course which further research could more clearly delineate.

Figure 14

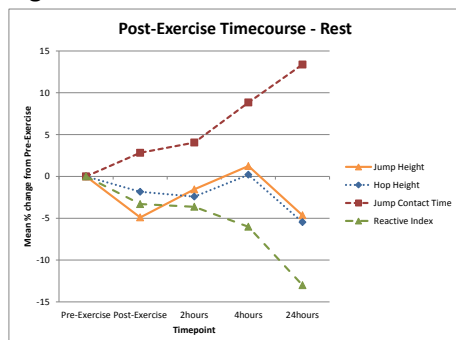
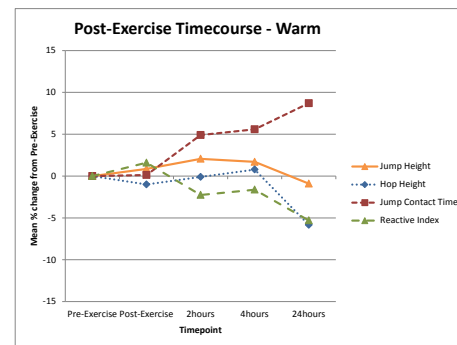
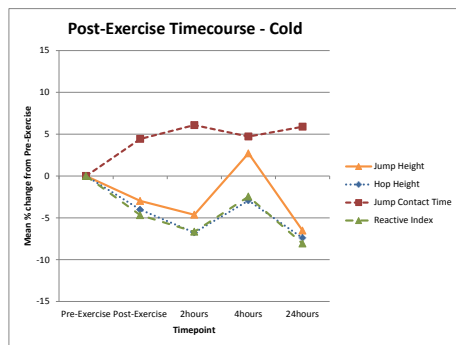


Figure 15

Figure 16

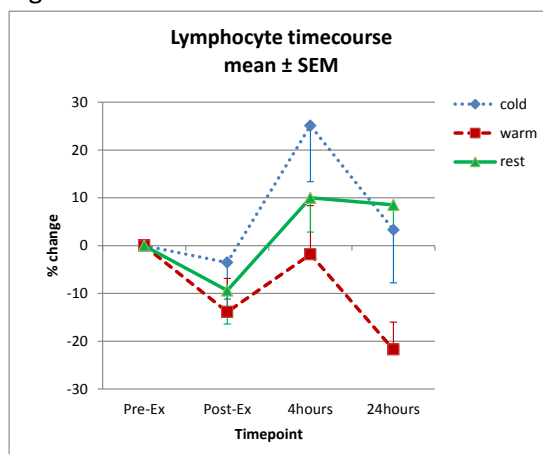


Compared with Pre-Exercise, decrements in the control condition of rest indicate incomplete recovery without intervention. On this basis, it appeared that all variables had recovered by 4 hours Post-Exercise, but that a decrement emerged at 24 hours in Jump Contact Time, Reactive Index, and Jump Peak Power_{pos}. With the control condition returned to a Pre-Exercise state, decrements following cold water immersion were evident in Jump Height, Jump Flight Time, Hop Height, Hop Flight Time and Jump Work_{pos}. Some decrements were at 2 and 4 hours post-exercise and stronger indications at 24 hours. This is consistent with hypothesis that cold water immersion has a detrimental effect on recovery.

The results showed a general pattern of emerging decrements in either the rest or cold conditions. At the 99% confidence interval (with correction for multiple comparisons), there was no difference between the Pre-Exercise state and 24 hours following warm water immersion in any measure of neuromuscular function. Where rest had not recovered, this suggests that warm water immersion avoided the emerging next-day decrement in Jump Contact Time and Reactive Index. It also strongly suggests there is no detrimental effect of warm water immersion.

At 4 hours compared to rest, lymphocytes were increased following cold water immersion and decreased following warm water immersion. There was a significant decrease at 24 hours following warm water immersion, illustrated in Figure 17. The relevance and implications of this are unclear.

Figure 17



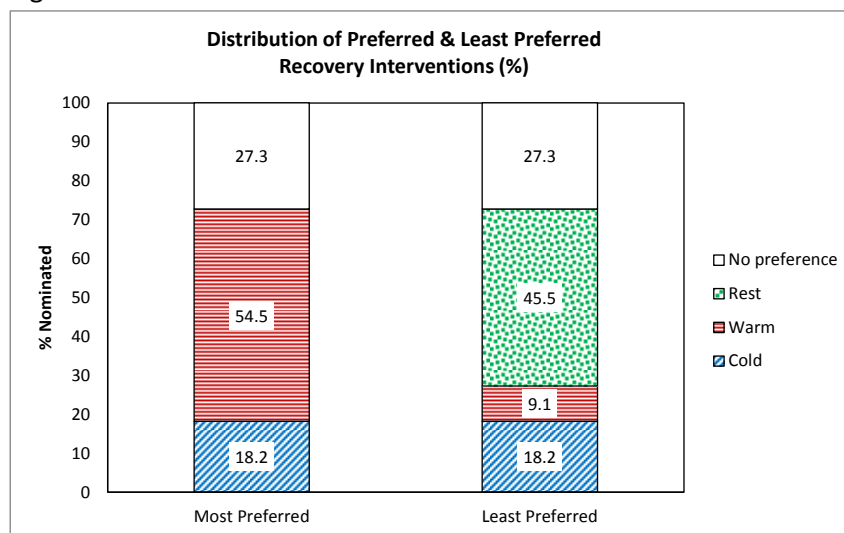
The observation of complete recovery at 2 or 4 hours and emerging decrements in next-day neuromuscular function is worthy of further exploration. This could be attributable to incomplete physiological recovery, contribution of other variables to neuromuscular function that have a different recovery time-course to those in this study; or inadequate warm up. The control group and standardised warm up should have countered any influence on the conclusions of this study, however the implications for recovery and same-day versus next-day warm-up practice warrant further investigation.

The importance of these observations should not be overstated. Exploratory variables showed no significant main effect of intervention or a time-intervention interaction. These variables were less sensitive to change over time compared to the main variables which showed post-exercise change, change over the recovery time-course and trended more predictably towards a pre-exercise state. Furthermore several of the exploratory variables are related, although the pattern of findings was consistent between Jump and Hop skills (Height and Flight Time).

Preferred intervention

Figure 18 illustrates the distribution of nominated Preferred and Least Preferred recovery interventions. Warm water immersion was the most preferred recovery intervention (54.5%). No subjects preferred rest, which was also the least preferred (45.5%) recovery intervention. Cold water immersion was Preferred and Least Preferred with equal frequency (18.2%).

Figure 18:



Correlation between outcome measures

The correlation between physiological, functional, measures of perception and athletic performance is an important step in proposing the clinical relevance of scientific findings and making recommendations for practice. Changes in performance are unlikely the result of a single key variable (Barden & Kell, 2009). It is valuable to scrutinise the clinical efficacy of water immersion practice based on several variables, which when combined, provide an indication of performance potential.

Table 5 shows the rank-ordered significant correlations between selected physiological and perceived recovery measures. The strongest correlations were between PF and PR ($r=-.87$), Jump Height and Work_{abs} ($r=.70$), PF and neutrophils ($r=.56$), PR and neutrophils ($r=-.51$), PF and leukocytes ($r=.50$). Correlations between KF Peak Torque, KE Peak Torque, Jump Height and Jump Work_{abs} were all $r>.47$.

Table 5 Rank-ordered variables with significant correlation

Strength category	Variables	Pearson's <i>r</i>	<i>p</i>	sig level
Strong	PF & PR	-.87	.000	.01
	Jump Height & Work abs	.70	.000	
	PF & neutrophils	.56	.000	
	PR & neutrophils	-.51	.000	
	PF & leukocytes	.50	.000	
Moderate	KF Peak torque & Jump Work abs	.49	.000	
	KE Peak Torque & Jump Height	.47	.000	
	KE Peak Torque & Jump Work abs	.47	.000	
	PF & MYO	.43	.000	
	PR & Leukocytes	-.43	.000	
	PR & MYO	-.37	.002	
	PR & Hop Work abs	.36	.003	
	KF Peak Torque & Myoglobin	-.36	.003	
	KF Peak Torque & Jump Height	.34	.005	
	KF Peak Torque & Jump Work neg	.34	.006	
	KF Peak Torque & CK	-.34	.006	
	KF peak torque & PR	.34	.005	
	KE Peak Torque & Hop Work abs	.34	.005	
	PF & CK	.32	.011	
Small	PF & Jump Work neg	-.26	.042	.05
	PF & Hop Work abs	-.26	.039	
	KF Peak Torque & Neutrophils	-.26	.038	
	KF Peak torque & Perceived Recovery	.25	.040	

RESEARCH QUESTIONS ANSWERED

The research questions sought to establish the effects of water immersion on physiological recovery, neuromuscular recovery and perceived recovery; and to establish whether there is a relationship between these measures, as indicators of overall athlete recovery.

There was no significant effect of water immersion on physiological recovery, indicated by no main effect of intervention on any variable. Regardless of intervention, serum indices of leukocytes, neutrophils, CK and myoglobin had not recovered by 4 hours post-exercise, although all but CK had returned to pre-exercise levels by 24 hours.

The effects of water immersion on neuromuscular function were less discrete. Warren et al., (1999) argue that while pain and ratings of muscle soreness are important, the primary focus of intervention should be upon restoration of function. This could be underpinned by restoration of physiological conditions which facilitate maximum functional performance, which supports integrated consideration of the outcome measure spectrum to draw an overarching conclusion.

However it could also be interpreted that functional measures are of most importance in clinical decision making. KF Peak Torque & Jump Work_{abs} could therefore receive greatest weighting based on their sensitivity to post-exercise change, stability over time and correlation with the functional performance of Jump Height. Jump Work_{abs} had not returned to a pre-exercise state by 4 hours without intervention but had returned by 2 hours following warm and cold water immersion. KF Peak Torque had not returned to a pre-exercise state by 24 hours without intervention, but had returned by 4 hours following cold water immersion and 24 hours following cold and warm water immersion. These findings were acceptable at the 95% certainty level without correction for multiple comparisons. The interpretation is plausible, clinically relevant: at 2 hours post-exercise, water immersion is likely to facilitate the recovery of Jump Work_{abs}. Cold water immersion is likely to facilitate the recovery of KF Peak Torque at 2 and 4 hours; and both cold and warm water immersion is likely to facilitate its recovery by 24 hours.

This is also consistent with perceived recovery: water immersion facilitated PR at 2 hours post exercise with 99% certainty. PF was not different to post-exercise until 24 hours without intervention, but was lower at 2 and 4 hours following cold and warm water immersion with 99% certainty. Lower average PF and higher average PR ratings followed cold water immersion at every time-point. Warm water immersion was the most preferred recovery intervention and passive rest was the least preferred. Cold water immersion was nominated with equal frequency as most preferred or least preferred recovery condition.

Exploratory variables indicated further evaluation of the recovery time-course of neuromuscular function would be worthwhile, in particular the pattern of decline in next-day functional performance. It was possible that water immersion, particularly cold, impaired the recovery of KE Peak Torque, Hop Height and Hop Flight Time. However the relevance of these observations are unclear as these variables did not provide stable measure and the underpinning mechanisms do not rationalise a detrimental effect of thermo-neutral water immersion.

CONCLUSION

There was a strong correlation between the reciprocal PF and PR. Jump Work_{abs} and KF Peak Torque were the most reasonable functional performance indicators given their significant post-exercise decrement and correlation with Jump Height. Although functional measures may be considered most relevant to performance, these results showed PR & PF correlated more strongly with leukocytes & the neutrophil subpopulation, and myoglobin. These strong correlations and multiple further moderate correlations between serum indices, functional performance and perceptual measures support the proposition that fatigue and performance are integrated multi-system constructs, and the outcome measures of this study provided a relevant representative measurement spectrum.

Although water immersion effected some variables, based on the balance of these results and statistical significance the null hypotheses were accepted; that there was no main effect of 5 minutes of water immersion on overall athlete recovery from intense exercise. There was no detrimental effect of cold water immersion on muscle function two hours after immersion.

Further research with larger subject numbers could elucidate clinically relevant observations in the post-intervention recovery time-course. If there is an effect of water immersion on athlete recovery it is likely to be small.

Appendix 4 – Expert consultation: Common interview format

Clinical implications for water immersion practice Common Interview Format

Location, time, date:

Expert identification number:

Introduction

Welcome & appreciation of their time

Review the interview objectives:

1. To determine the water immersion practice implications of the findings of this study.
2. To explore the mechanisms of clinical decision making and how the evidence is valued and applied by practice experts.

Explain that the session will be recorded by scribe

There is no right answer to the questions

Your views FIRST, then introduce mine to the discussion

Overview of agenda

- Your current advice to athletes on water immersion recovery
- The reasons underpinning your advice
- Your views on the research brief
- Identify & discuss emerging issues
- Further research questions
- Closure on key viewpoints

1. Introduction:

What is your professional discipline?

You manage professional athletes in sports of.....

2. Current water immersion practice

How often do you advise athletes on water immersion recovery practice?

What is your general advice?

Does it differ post-training versus post-competition?

Does it depend on the timing of the next exercise bout?

Particularly:

- i) temperature protocol
- ii) immersion time
- iii) immersion depth

3. What is your advice based on? For example,

Your own reading / review of research?

Guidelines recommended by others (eg colleagues; a particular study; NGB)

Your experience of what works best

Athlete preference

Scheduling / timing logistics

Resource availability

What characteristics determine how you apply evidence to your practice?

Eg. degree of certainty of findings, balance of cost / benefits, how you value the information

source? (from trusted colleague vs conference vs published article)

4. Discuss your response to the research brief

Answer any further questions relating to the study / results

What are the key findings for you?

What are the key implications for your practice?

Would you change your practice?

How / why / why not?

5. Further research questions

Has this brief generated further research questions for you?

What are key issues you would like answered to inform your practice?

6. Emerging issues

Discussion of common themes across expert consultation

7. Closure on viewpoints / key conclusions

Recommendations for water immersion practice

Based upon.....